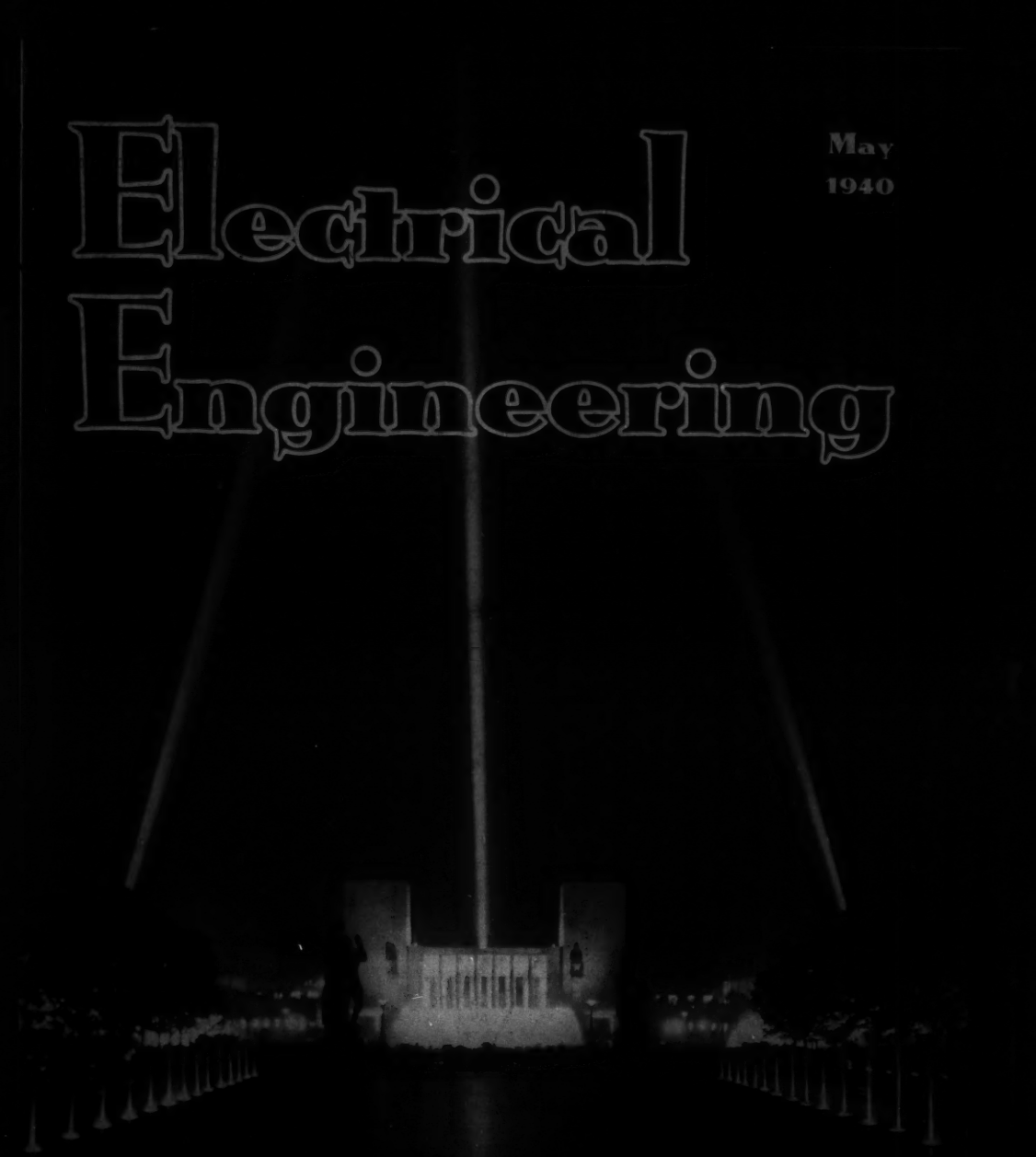
Electrical Engineering

May
1940



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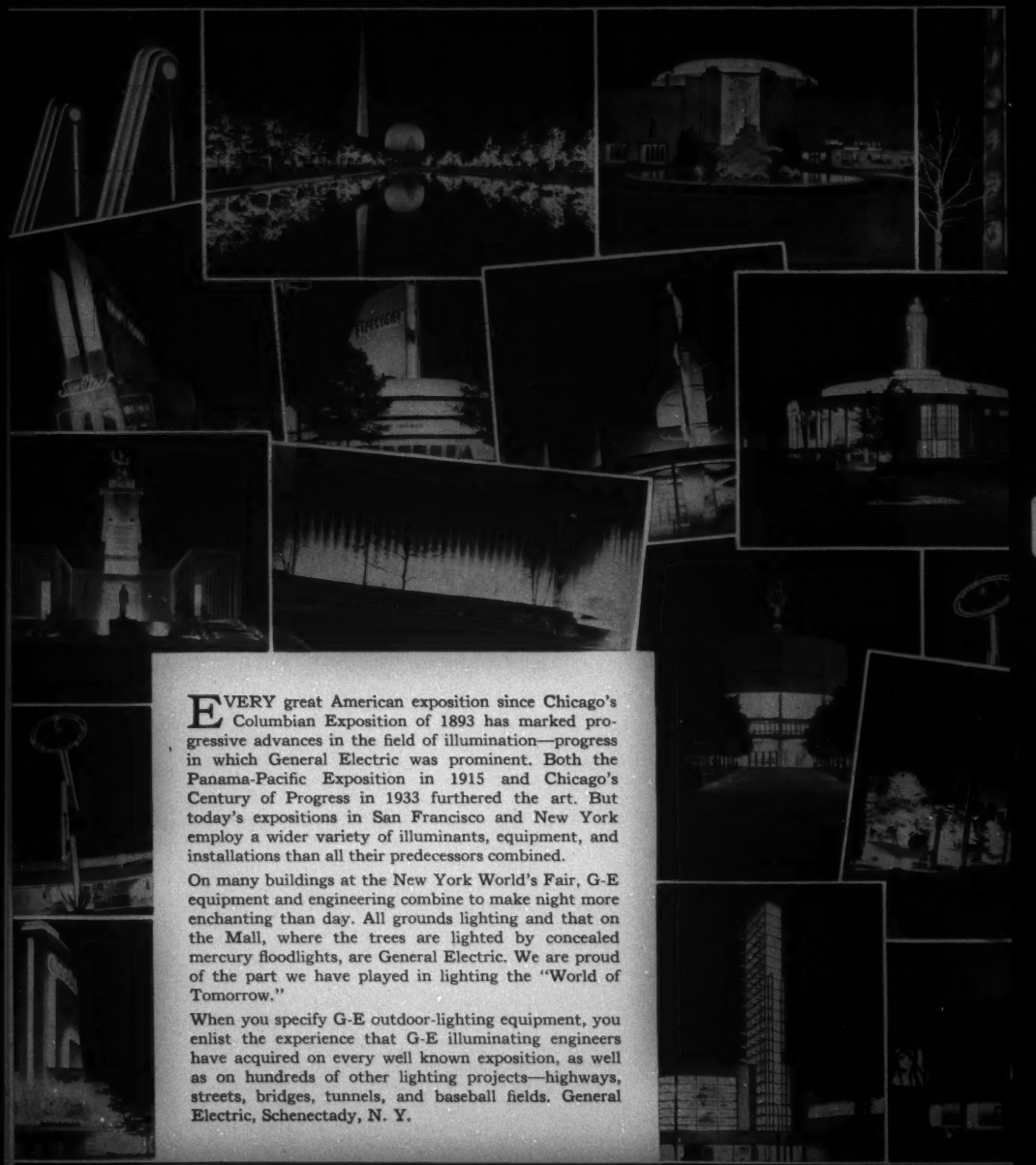


EVERY great American exposition since Chicago's Columbian Exposition of 1893 has marked progressive advances in the field of illumination—progress in which General Electric was prominent. Both the Panama-Pacific Exposition in 1915 and Chicago's Century of Progress in 1933 furthered the art. But today's expositions in San Francisco and New York employ a wider variety of illuminants, equipment, and installations than all their predecessors combined.

On many buildings at the New York World's Fair, G-E equipment and engineering combine to make night more enchanting than day. All grounds lighting and that on the Mall, where the trees are lighted by concealed mercury floodlights, are General Electric. We are proud of the part we have played in lighting the "World of Tomorrow."

When you specify G-E outdoor-lighting equipment, you enlist the experience that G-E illuminating engineers have acquired on every well known exposition, as well as on hundreds of other lighting projects—highways, streets, bridges, tunnels, and baseball fields. General Electric, Schenectady, N. Y.

GENERAL ELECTRIC

What every buyer of enameled wire should know about the advantages of *Balanced* insulation

THE ADHERENCE TEST is one of several standard tests which measure the Balanced Quality of enameled wire insulations

Dropping the weight to stretch the enameled wire between movable clamps.

Measuring the elongated distance between marked points on enamel film.

Good enameled wires must possess many specific characteristics to withstand the routine treatment imposed during winding operations . . . . . Quantitative tests are now available to measure these characteristics and afford an overall rating for Balanced insulation.

• • •

HOW ADHERENCE TESTS REVEAL DEFECTIVE INSULATION

An adherence test measures the ability of any enamel film to adhere to the surface of a conductor when it is elongated by the stresses encountered during coil winding operations.

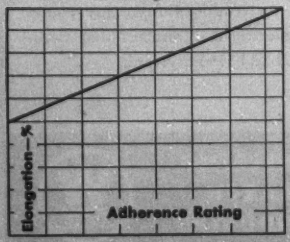
The Belden Adherence Tester is a standard test instrument, perfected by Belden engineers, which holds a test sample of enameled wire between two clamps. The upper (fixed) clamp is attached to the two inner vertical rods. The lower (movable) clamp slides on the inner rods and is straddled by a yoke. Above the yoke is a sliding impact weight.

Two marks are scratched on the enameled wire and the distance between them noted. The impact weight is then dropped on the yoke which drives the lower clamp downward and stretches the test sample. After the elongation is measured, the enamel film is examined for cracking and flaking. The amount of elongation is controlled by the setting of the lower clamp.

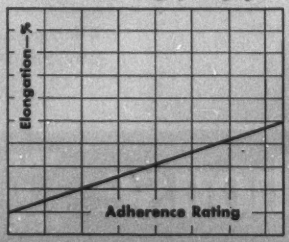
To detect the presence of harmful driers in the enamel film, other samples are preheated to impregnating and baking temperatures and then tested for adherence. Comparison with standard adherence curves indicates the adherence rating of the film.

All Belden enameled wires must pass these strenuous adherence tests. Only "balanced" insulation will survive them. Adopt these tests and eliminate guesswork when you are looking for "balanced" insulation.

Adherence Rating at 78° Fahr.



Adherence Rating after Aging



WHAT IS BALANCED INSULATION?

Balanced insulation means an enamel film which offers the best OVERALL performance. Such important characteristics as abrasion-resistance, flexibility, adherence, aging, solvent-resistance, etc., must be balanced against each other. None must be too high nor too low. All must be evenly balanced.

It is easy to make enameled wire that will rate high in one or two of these essential qualities. But, too often, a high individual rating for one quality reduces the ratings of other qualities. For example, an overbaked enamel usually has high abrasion-resistance . . . but its flexibility is low. Or a very flexible film may not resist the action of solvents.

The ideal combination is found only in a wire with Balanced insulation . . . like Beldenamel. Beldenamel is made under such accurately controlled conditions that the essential electrical and mechanical characteristics are scientifically balanced. They are "balanced" to give you the most satisfactory results in your winding department . . . and in your finished product.

Why not adopt Belden test methods and be sure you are getting "balanced" insulation? They apply to all types of enameled wire.

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Successful duplication of natural lightning in the laboratory permitted Westinghouse engineers to study transformer protection problems as they actually exist in service. As a result, improvement after improvement was made including the introduction of "De-ion" gaps which not only give full lightning protection but also eliminate fuses.

As additional insurance of complete self protection in actual service, Westinghouse literally put lightning on the production line to surge test each finished C-S-P transformer. The Westinghouse seal of approval on each C-S-P transformer states the amperes and kv:ms at which it is direct-stroke tested.

Further proof of C-S-P perfection is revealed by the records of a thousand power companies, which show that the new Westinghouse transformers provide 99.66% perfect protection against service interruptions from any cause. Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pennsylvania.

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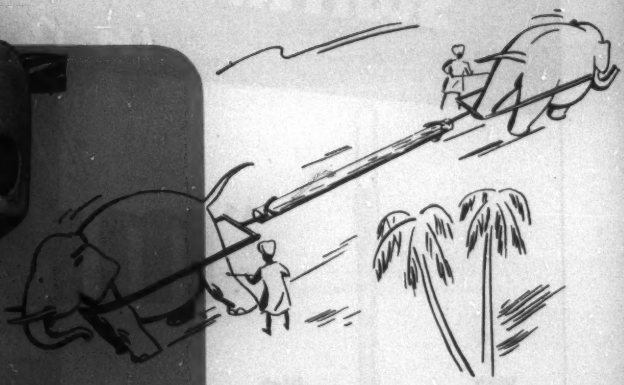
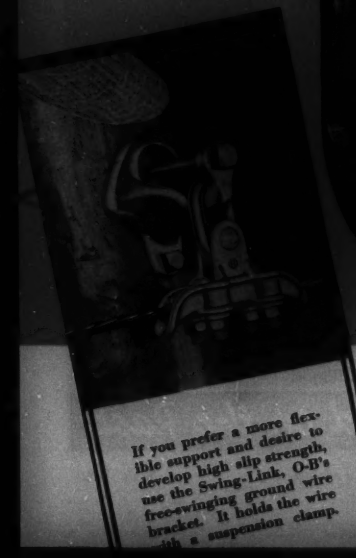
How to Stretch a Pole 6 Inches



● Sounds impossible, but to add to the height *in effect* you simply install an O-B Clamptop ground wire bracket. Using a clamp mounted on *top* of the device this bracket permits an increase of spacing between ground wire and conductors of 6 inches or more over any other designs, assuming the same bolt hole is used. As shown in the illustrations, the bracket is available for either wood poles or steel towers. And another big advantage is that a ground wire can be transferred directly from stringing blocks to the clamp, thus making the job of stringing quicker and easier. Before equipping any lines for ground wires, investigate this bracket. You'll find its use is justified by either the greater spacing or easier stringing.



If you prefer a more flexible support and desire to develop high slip strength, use the Swing-Link, O-B's free-swinging ground wire bracket. It holds the wire with a suspension clamp.

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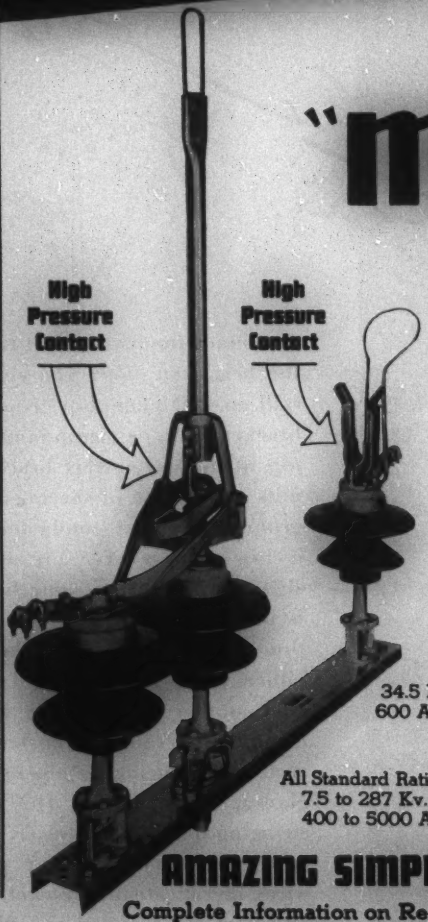

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for May 1940—

The Cover: Searchlight beams form a canopy over the Court of Peace and Lagoon of Nations at the New York World's Fair, which opens for its second season May 11. Fair illumination, which utilizes new light sources and new materials, is described in this issue.

Photo courtesy General Electric Company

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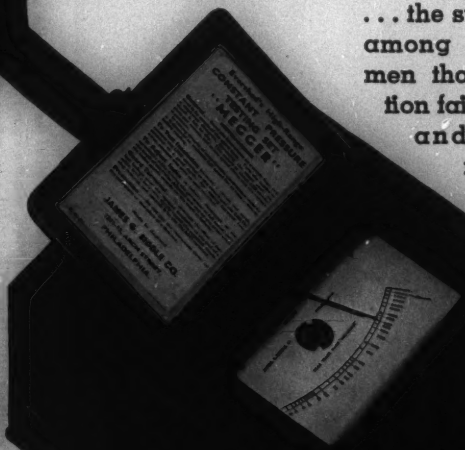

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Courtesy N. Y. World's Fair

Figure 1. An air view showing most of the 1,216-acre area of the New York World's Fair, and essentially all of the main exhibit area. The focal points marked are: (A) Court of Peace, government area; (B) Lagoon of Nations fountain; (C) Constitution Mall, with the Four Freedoms plaza (toward the Lagoon) and the heroic George Washington statue facing the Menship fountain and the Perisphere; (D) Theme Center with surrounding plaza; (E) New York City Building, one of the permanent structures; (F) transportation zone, marine and air at the right, automotive at the center, railroads at the left; (G) Bowling Green plaza; (H) Court of Communications; (I) Court of Power; (J) Plaza of Light, electrical-manufacturing and utilities zone; (K) amusement zone starts here and extends to the right. To help readers to orient themselves, the points from which the eight color views were photographed are indicated by numerals, which correspond to the plate numbers

Lighting the New York World's Fair

RICHARD C. ENGELKEN*
MEMBER AIEE

THE CONVERSION of more than 1,200 acres of salt marsh and waste land into the New York World's Fair, with its stimulating review of the world of today and its effective preview of the "World of Tomorrow," was a remarkable achievement, accomplished within the short span of three years. In this $150,000,000 transformation, electric light played a major role. Also, the Fair provided the stimulus that brought from the laboratories into commercial production some of the most significant developments ever made in the field of artificial illumination.

The magnitude and magnificence of the New York World's Fair resulted from the combined efforts of many minds and countless hands, all deserving of commendation. Accomplishments, however, mirror capable direction, for which special mention is made of Chairman Stephen F. Voorhees of the Fair's Board of Design, and Colonel John P. Hogan, chief engineer and director of construction. Illumination was headed by Bassett Jones, consulting engineer to the Board of Design, working with J. S. Hamel and the author as lighting consultants to the construction department. The problem of developing the spectacular displays for the Fair was delegated to a Committee on Displays which reported to the Board of Design. This committee was headed by Bassett Jones, and included Professor Jean Labatut, design; Howard Cooper, hydraulics; and the author, lighting. Operation of spectacles was headed by A. K. Morgan, director of displays.

GENERAL FEATURES

The exhibit area (figure 1) comprising about 1,000 acres, contains more than 200 structures, most of which are windowless exhibit buildings. A zoning and color scheme adopted prior to construction insured architectural unity, and harmony of plan, design, and treatment throughout the whole area. Seven classified zones (foods, governmental, distribution, communication, transportation, community interests, and business administration) are distributed around the Theme Center, with streets radiating from the center and crossed by circumferential avenues. The color scheme, also zoned, but on a basis of aesthetic values rather than occupancy zoning, is co-ordinated with the physical layout. Starting with white at the Theme Center, color treatments of red, blue, or gold radiate outward with progressively more saturated hues. Adjoining hues blend circumferentially along the avenues. By virtue of the proper selection of accents and relief tones, each structure presents a color scheme of interest in itself as well as appropriate to the general picture. The illumination was so fitted into this scheme as to maintain the basic pattern by night as well as by day, but with a new and added interest and charm after sunset (see color plates).

Thus illumination and lighting effects became definite elements in the architecture of Fair buildings. As part of the general plan, the exterior surfaces of the buildings themselves serve as major sources of illumination for adjacent street and plaza areas (figures 41–56; color plates). Brightly lighted entrances, niches, and murals, and backlighted plaques aid in effectively achieving this result. With few exceptions, street lights are used to complete the decorative effects rather than as primary sources of illumination (figures 68, 69).

In building interiors, unobtrusive built-in fixtures in general provide simple decorative effects and good aisle lighting with increased intensities at entrances and exits (figures 57–67). This allows exhibit lighting to be arranged to suit individual requirements.

To give the Fair a pleasingly varied skyline at night and to produce a desirable air of festivity, several tall and brilliantly lighted architectural features such as the pylons were provided for in the illumination scheme (color plates and figures 32–40). Also, the various courts and plazas contain suitable small architectural forms combined with the elements of water, light, and flame to produce scintillating animated effects by virtue of the combination of new elements and materials rather than by mere cyclic color variations. Finally, there were the outstanding "spectacles": the Perisphere-Trylon, Constitution Mall, the Lagoon of Nations, the Court of Peace with its canopy of searchlight beams, and the combined light and fireworks display in Fountain Lake in the amusement area.

Obviously the successful completion of such a gigantic plan required not only the most exacting co-ordination and the closest co-operation among the many architects, engineers, constructors, landscapers, and others involved, but also the creating of new structural forms and new types of lighting equipment. To provide the necessary focal point for technical co-ordination, a test laboratory was established on the Fair grounds in the earliest stages of its development. This served as a medium of contact for the many different interested agencies, and also afforded facilities for research and the study of illumination sources and their possible uses.

Experiments performed in this laboratory served as a stimulus for the commercial development of many new light sources which at that time were found only in the lighting research laboratories. Also many entirely new lighting devices were designed there for the effective application of these new sources. Typical instances are the now well-known low-voltage fluorescent lamp and the high-intensity mercury capillary lamps, which were first used extensively at the New York World's Fair. Architectural

* Member of the firm of Morgan, Hamel, and Engelken, lighting consultants to the New York World's Fair 1939.

elements to utilize new and existing light sources also were developed, or inspired by scale models giving a visible concept of their possibilities.

To insure architectural harmony and unity of effect, all general structural plans, including exterior lighting for private exhibit buildings as well as Fair projects, were first submitted for approval to the World's Fair Board of Design. Thereby the master plan was consistently sustained.

Space limitations preclude adequate description of any appreciable proportion of the many points of engineering and illumination interest throughout the Fair grounds. Therefore, the scope of this article is limited primarily to the "spectacles" which constitute the backbone of the "picture" presented by the Fair at night, and secondarily to typical details embracing the effective application of new light sources, including the material and equipment involved in those applications.

Theme Center

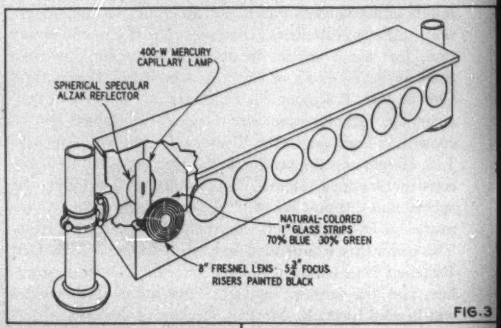
Because of the importance of the Perisphere-Trylon Theme Center in the general scheme of the Fair, special efforts were exercised to make it as unusual in its nighttime illumination, as it is unique in daytime by virtue of its novel architectural design (plates II and IV). Aside from aviation warning lights at its apex and at points on its sides, the 700-foot Trylon is illuminated only by spill light from adjacent structures.

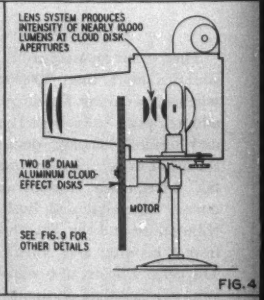
The Perisphere, a 180-foot spherical structural part of the Theme Center, presented a lighting problem of unprecedented nature and proportions. The illuminating-engineering job of making an appropriate and attractive nighttime spectacle out of this huge ball paralleled the mechanical-engineering job of delicately poising a 4,600-ton steel-framed concrete "bubble" over a shallow mirror-pool of water. The exterior lighting problem involved facilities for flooding this sphere with suitable intensities of either amber, red, or blue light, and the further problem of projecting moving cloud patterns over its three-acre surface (plate IV). Even the floodlighting had to be accomplished by lens-controlled light-beam projection, because the roofs of the nearest buildings on which lighting units could be placed were some 250 feet away (figure 13).

Based upon extensive experimenting with scale models using a six-foot-diameter wooden ball painted white as a model, the lighting sequence adopted is an amber light thrown on as dusk approaches, subsequently fading into a sunset red, and then into a deep evening blue after dark. Water jets underneath the Perisphere, supplemented by blue floodlights beneath the surface of the reflecting pool, and white cloud-shapes projected onto the Perisphere combine to impart the desired effect—that of a translucent bubble poised over the surface of its reflecting pool.

Three types of projectors are used for the exterior floodlighting of the Perisphere. For the amber and red light, projector units of the Fresnel type fitted with 5,000-watt incandescent lamps are used (figure 5). Banks of 8 of these units, 4 red-beam projectors and 4 amber, are mounted on the roof of each of the 5 buildings selected as projection points, making a total of 40 units (figure 2).

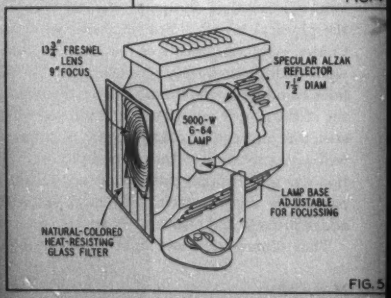
The production of an adequate intensity of blue light on the extensive surface of the Perisphere presented a major problem in illumination and required the development of a new light source and related equipment for its use. Because of the blue deficiency of an incandescent light source, a 400-watt high-intensity short-arc mercury capillary lamp was developed and special projectors were designed for the


400-W MERCURY CAPILLARY LAMP
SPHERICAL SPECULAR ALZAK REFLECTOR
NATURAL-COLORED 1" GLASS STRIPS 70% BLUE 30% GREEN
8" FRESNEL LENS · 5 3/4" FOCUS
RISERS PAINTED BLACK
FIG. 3


LENS SYSTEM PRODUCES INTENSITY OF NEARLY 10,000 LUMENS AT CLOUD DISK APERTURES
TWO 18" DIAM ALUMINUM CLOUD-EFFECT DISKS
MOTOR
SEE FIG. 9 FOR OTHER DETAILS
FIG. 4

Figures 2–5. The three-acre exterior surface of the Perisphere is illuminated in any of three colors by 30 nine-lamp projectors using mercury capillary lamps with Fresnel lenses ribbed at the back to give a 10-degree horizontal spread (3) and 40 5-kw incandescent projectors, 20 red and 20 amber (5), drifting clouds are produced by 30 2.5-kw incandescent cloud projectors (4). This equipment is installed on the roofs (2) of five buildings around the Theme Center

FIG. 2


13 3/4" FRESNEL LENS 9" FOCUS
SPECULAR ALZAK REFLECTOR 7 1/2" DIAM
5000-W G-64 LAMP
LAMP BASE ADJUSTABLE FOR FOCUSSING
NATURAL-COLORED HEAT-RESISTING GLASS FILTER
FIG. 5

job. Each of these projector units accommodates nine of the new 400-watt mercury lamps, with suitable light-control optics (figure 3). Blue light for the underside of the Perisphere is provided by 96 blue-filter submerged projectors (similar to those of figure 17) using the new 100-watt mercury capillary reflector lamps.

Cloud projection, relatively simple with the 6-foot model, became another major problem when applied to the three-acre surface of the 180-foot Perisphere. To produce the misty cloud effect desired, an illumination intensity of nearly 10,000 lumens through the projector gate and objective lens is necessary. The resulting intense heat in the projector gate precludes the use of any photographic emulsion or ordinary painted slide; in fact, even the regular mica cloud-machine disks buckled and cracked from the heat. By experiment it was found that aluminum disks containing irregularly shaped apertures backed by small pieces of mica could be used, and that a heat-resisting paint could be applied to the mica to provide gradation in shadows. In the final installation, two such

Figures 6–12. Inside the Perisphere (11, 12) "Democracity" is illuminated by a continuous strip of floodlight projectors underneath the lower platform (6), another continuous strip illuminates the horizon (6). Sky lighting is provided by a separate row of projectors (10), moving clouds are thrown across the sky by special cloud projectors (9) and their companion shadows across the landscape by special shadow projectors (8). The night scene is complete with stars (7) representing the principal constellations as they appeared in nature. The motion-picture murals (12) are produced by ten special projectors (11, unlabeled unit)

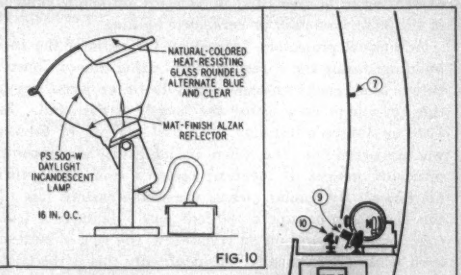
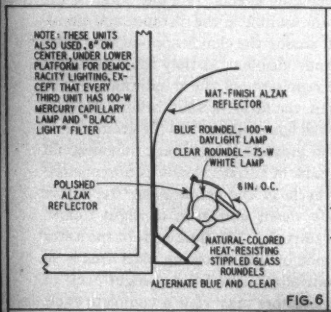


FIG. 10


NOTE: THESE UNITS ALSO USED 8' ON CENTER UNDER LOWER PLATFORM FOR DEMOCRACITY LIGHTING, EXCEPT THAT EVERY THIRD UNIT HAS 100-W MERCURY CAPILLARY LAMP AND "BLACK LIGHT" FILTER
MAT-FINISH ALZAK REFLECTOR
BLUE ROUNDEL – 100-W DAYLIGHT LAMP
CLEAR ROUNDEL – 75-W WHITE LAMP
6 IN. O.C.
POLISHED ALZAK REFLECTOR
NATURAL-COLORED HEAT-RESISTING STIPPLED GLASS ROUNDELS
ALTERNATE BLUE AND CLEAR
FIG. 6

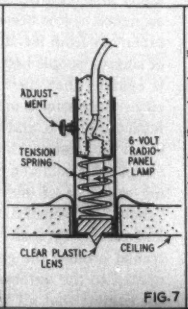


FIG. 7

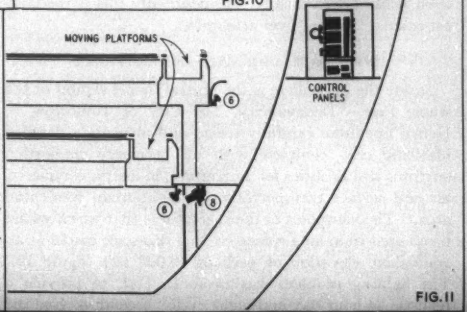


FIG. 11

Courtesy Henry Dreyfuss

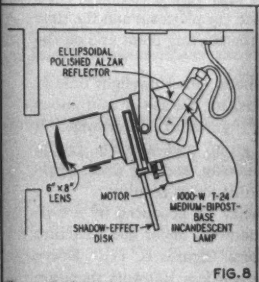


FIG. 8

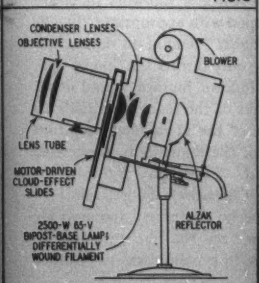
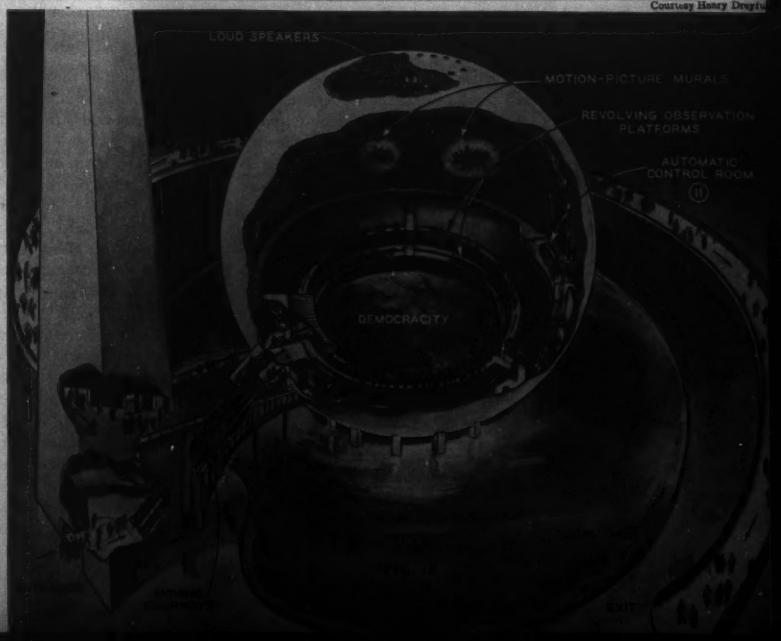


FIG. 9



mica-backed aluminum disks rotating at different speeds are used in each projector (figures 2, 4). Thirty of these cloud-projectors, each using a 2,500-watt high-color-temperature tungsten lamp, are used with overlapping patterns to cover the whole visible area of the Perisphere.

All projectors—amber, red, and blue floodlighting units and cloud machines—are connected to reactance-dimmers and preselective control equipment which permit any cycle of lighting to be used, and provide for automatic control of the 383 kw of exterior Perisphere lighting.

Additional projectors, located on the roofs of the two buildings facing the Perisphere from either side of Constitution Mall, enable special effects to be projected upon the Perisphere area facing the length of the Mall. In 1939 on Edison's birthday, a 75-foot portrait of Edison was projected onto the sphere by additively superposing projected images of identical pictures from these two machines. By similar means, the whole eastern face of the Perisphere became a 180-foot jack-o'-lantern in true color and configuration on Halloween; the jack-o'-lantern even winked occasionally. Undoubtedly this is the largest colored "movie" ever attempted.

INTERIOR ILLUMINATION OF PERISPHERE

Inside the Perisphere is the central theme exhibit of the whole Fair—"Democracity, The City of Tomorrow"—Henry Dreyfuss' carefully scaled and intricately detailed idealistic city, complete with all necessary supporting environs and facilities for agriculture, industry, commerce, air and surface transportation, and suburban residential area. The viewpoint of the spectator is that which would be secured from an airplane circling this scale model at an equivalent elevation of perhaps 10,000 feet (figure 12). The lighting problem was twofold: first, to provide a realistic 24-hour day-and-night cycle; second, to give the observer the physical impression of being suspended in space with the earth beneath him and the sky overhead extending to distant horizons.

The illumination problems encountered in the accomplishment of the desired results in the Perisphere interior, which is actually a large integrating sphere, were found to be even more exacting than those encountered on the outside. Frequent, rapid, and smooth changes in lighting effects are required, as well as exact synchronization of these visual effects with recorded sound effects ranging from voice to music; all automatically controlled in predetermined accurately timed repetitive cycles.

Spectators enter the exhibit through the base of the Trylon, and by means of the two longest (96 feet and 120 feet) electrically operated moving stairways built to date are carried up either 48 feet or 60 feet, respectively, to the lower or upper of two continuous electrically operated moving platforms that carry the spectators at a predetermined speed around the inside periphery, just below the equator of the Perisphere globe.

If the spectator happens to arrive during the day scene, he sees below him in bright "sunlight" the miniature scale City of Tomorrow and its supporting countryside stretching to far horizons and blending realistically with the "sky." Above him is the tremendous arched dome of the Perisphere, impressive in its resemblance to the sky, floodlighted unobtrusively in blue, giving the impression of the heavens complete with moving clouds and their companion shadows drifting across the buildings and landscape. The scene gradually changes, shadows actually lengthen to afternoon proportions, daylight fades smoothly and realistically into dusk, and the sky gradually becomes a midnight blue. Above in the seemingly limitless depths of the vaulted dome appear stars, including those accurately representing the major constellations as they appeared in nature on the night of April 30, 1939, when the Fair first opened. Night clouds drift across the sky. In the meantime, lights have appeared gradually and unobtrusively in the city, in the neighboring industrial area, and in the nearby community of small homes. As the night cycle progresses, the countryside becomes dark except for a few lighted windows and the illuminated highways.

Against a background of appropriate music, the voice of a commentator explains the symbolism of the changing scenes, and helps the spectator to note and follow the many and realistic changing effects. At one stage of the sequence, voices become audible in the distance and simultaneously from far off among the clouds approaching hosts of singing people become visible. As they come nearer, it is evident that they represent all the inhabitants of the city—the business men, the farmers, the workers, the professional people, and the housewives. As the groups draw closer and assume their greatest proportions, they descend out of sight behind a bank of horizon clouds as the concluding sequence of one cycle in the continuously repetitive "show." Immediately dawn and then daylight follow, and another cycle has started. The time cycle of spectator transit around the globe on the revolving platforms is so related to the automatically controlled day-night cycle of the exhibit that all spectators may view a complete cycle between the time they step onto the platform and the time they find themselves back to the starting point and on the way out.

The lighting of the sky dome in either daylight blue or deep night blue is accomplished by the use of continuous rows of concealed strip lights (figures 10, 11) arranged in two circuit groups—a blue group and a white group. The blue lights are on continuously, and the white lights vary from black-out to full brilliance as required.

The lighting for "Democracity" is produced by a continuous row of strip lights mounted under the structure that carries the lower platform (figures 6, 11). Every third unit in that continuous row is a 100-watt short-arc mercury capillary lamp equipped with appropriate "black-light" filter. These "black lights" remain on during the entire show, but are effective only during the "night" period of the cycle, when the windows, highways, and other apparently "illuminated" parts of the model are made to fluoresce under the influence of the ultraviolet radiation from these lamps by virtue of the fluorescent paint with which these parts are coated. Thus, the "lighting" in Democracity at night actually is entirely fluorescent.

Principal features of the special equipment required for the Perisphere interior "show" are the ten specially designed projectors that operate in synchronism to produce

the 18- by 30-foot motion-picture "murals" in the "sky" (figure 12). These machines use Bantam-size glass slides in place of the successive film frames of ordinary motion-picture projectors. In each machine, a series of these slides is projected through four optical systems in succession. The slides are mounted on two 50-inch ring gears which revolve within the optical systems. Through a shutter arrangement in front of the objective lenses the slide images are cross-dissolved from one optical system to the next, producing a smooth motion with 8 images per second (as compared with 16 or 24 for standard motion-picture projectors). As intensity of light on the screen remains constant but for absorption by the slides, there can be no flicker regardless of the number of frames per second. It is a noteworthy achievement that the projections from the four individual optical systems of each machine can be registered so accurately in superposition on a screen 165 feet away as to produce a composite result of smooth and realistic motion. Each projector uses four 2,500-watt 65-volt lamps having differentially wound filaments similar to those used in the cloud machines, and is fitted with $f/2$ objective lenses of 8-inch focal length, the largest ever built for such a purpose. To keep all ten projectors in perfect synchronism, each is driven by a Selsyn motor equipped with a mercury damper; all in turn are driven by a common Selsyn generator.

The cloud projectors for the Perisphere interior are similar to those already described for the exterior, with the exception that a lower illumination intensity at the gate permits the use of tempered glass cloud slides (figure 9). Two six-inch cloud slides in each machine are mounted in frames eccentrically driven to produce a rolling effect of the projected clouds.

The entire Perisphere theme show—including the time, music, earth, sky, and voice elements—is entirely automatic, and timed to split-second accuracy. The various operations, including the many lighting circuits and ten special motion-picture projectors, involved in a typical operating cycle of 336 seconds are under the control of motor-driven cams which operate through one revolution and then stop for a few seconds awaiting the initiating impulse which starts each new show cycle. The single signal impulse which initiates each new cycle automatically originates from a notch cut in the sound film. Thermionic tubes constitute the nerve center of this equipment, controlled by the cams and in turn regulating saturable-core control reactors in each of the lighting circuits.

THEME-PLAZA ILLUMINATION

The desired composition of the vista looking toward the Theme Center from any of the five thoroughfares radiating therefrom involved the problem of preserving the full effect of the blue light and cloud effects on the Perisphere. In general, this result was accomplished by keeping all objects of relatively high brightness out of the field of view, and by effecting as much control as possible over the quantity of stray or spill light that would tend to fog the atmosphere and thus dilute the color effect of the Perisphere. The levels of illumination on the exteriors of exhibit buildings were kept low in the vicinity of the Theme Center, grading to higher intensities farther away. Brightly lighted pylons, fountains, and other accents were kept at the opposite ends of connecting courts and thoroughfares.

Around the Theme Plaza itself, the illumination of building façades is accomplished chiefly through the use of back-lighted sculptures (figure 49). These provide spots of visual interest and also provide adequate illumination for adjacent walks. Remaining illumination, aside from reflected light from the blue sphere itself, is provided by luminescent trees activated by mercury light.

Constitution Mall

Connecting the Theme Center and the Lagoon of Nations and constituting a portion of the main backbone of the Fair is Constitution Mall, a 2,000-foot tree-shaded esplanade built around a series of rectangular lagoons and reflecting pools (figure 1). Principal architectural feature of the Mall is the 55-foot statue of George Washington, which is lighted only by spill light from structures on either side of the esplanade. Nevertheless it is as prominent and effective a part of the nighttime picture of Constitution Mall as it is of the daytime vista. The statue is the work of the noted sculptor James Earl Fraser, designer of the AIEE Edison Medal. Other architectural features of the Mall are the Manship sundial, fountain, and associated sculpture group just off the Theme Plaza, and the "Four Freedoms" statues (representing freedoms of press, religion, assembly, and speech). Like the Washington statue, the Freedoms statues are illuminated only by spill light.

The lighting of the Mall creates a strikingly beautiful night effect (plates I, II). Along either side of the Mall for its entire length is a double row of 50-foot luminescent trees which constitute an effective part of the view after sundown and at the same time provide all illumination necessary for the main walkways. Supplementary lighting for walks adjacent to exhibit buildings is provided by light from building entrances, and from illuminated murals, plaques, and niches on the sides of the buildings.

Underneath each of the trees along the Mall, one of the new 250-watt short-arc mercury capillary lamps is set into the ground, in a suitable fixture fitted with a cylindrical metal collar which projects above the ground line for the dual purpose of controlling the side light and of protecting the fixture from physical damage (figures 13, 19). Under the influence of the peculiar radiation from these flood lamps, the leaves, twigs, and branches of the trees become luminous with a soft greenish glow, producing a beautiful effect. The same type of lighting also is applied to the trees in the Theme Center Plaza, the Court of Communication, and the Court of Power (figure 1). In all, some 360-odd trees are so lighted.

WATER LIGHTING

Another attractive feature of the lighting composition of the Mall is a variety of water-lighting effects, chief of which is the animated play of colored light and water in the Manship fountain at the head of the Mall (figure 13). The Manship fountain and associated sculptures are in-

tended to connote the passage of time (indicated by the sundial itself) and the moods of time affecting the human race. This latter effect is simulated by the alternate floods of gold light and blue light which seem to pour in repetitive cycles from three apertures in the abutment of the sundial terrace and flow in successive waves down the entire length of the pool in the layer of mist which overlies the pool. These effects are created by a cyclic play of light upon three columns of water which pour from the sundial abutment and upon curtains of mist overlying the pool. During the operation of the fountain, the columns of water flow continuously, the volume magnified by an ingenious arrangement (figure 16) that produces in actuality a relatively thin-walled cylinder of water 20 inches in diameter. Waterproof lighting units built into the central portion of the discharge "megaphones" of this fountain introduce into each water column alternate cycles of blue and gold light which grade smoothly from dark to maximum brilliance and back to dark for each color. In the pool of the fountain (figure 13) a set of continuous striplights (figure 17), on the center line of each of the three water columns, extends for a distance of approximately 115 feet. Flanking each of these striplights is a

Figures 13–19. The main esplanade of Constitution Mall (13, plate I) consists of reflecting pools lined with small illuminated water jets (17, plate II) and enlivened by several small back-lighted cascades (18). Broad tree-shaded promenades along either side are illuminated by the trees themselves, which luminesce under the influence of radiation from mercury capillary units, one underneath each tree (19). At the west end of the main esplanade is the Manship fountain with special mobile effects produced with water and light (13, 16, 17). Various illuminated murals (15) add decorative touches along the Mall, and in other parts of the grounds. The principal plazas are lighted by special projector standards (14) which concentrate the light on the ground, keeping it out of the range of vision

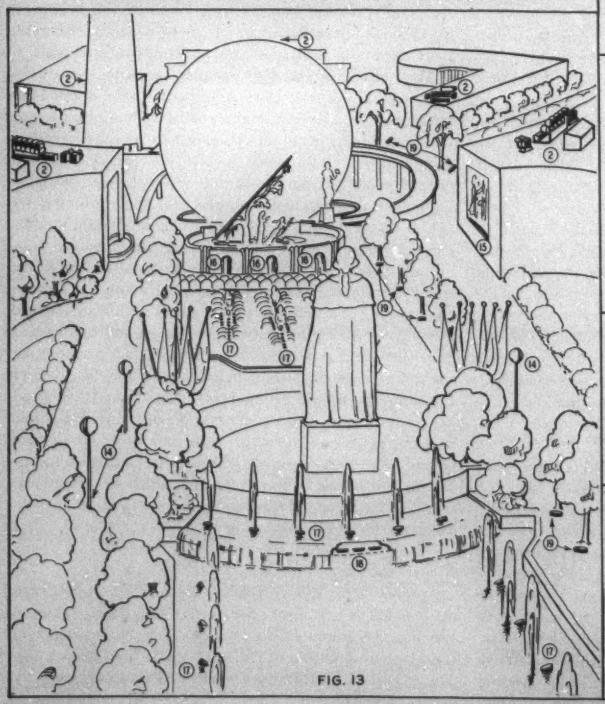


FIG. 13

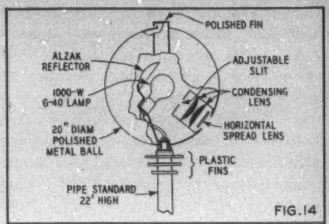


FIG. 14

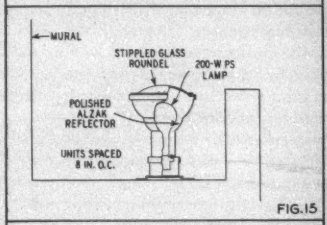


FIG. 15

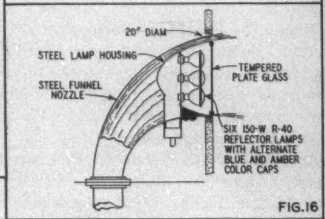

20" DIAM
STEEL LAMP HOUSING
TEMPERED PLATE GLASS
STEEL FUNNEL NOZZLE
SIX 150-W R-40 REFLECTOR LAMPS WITH ALTERNATE BLUE AND AMBER COLOR CAPS

FIG. 16

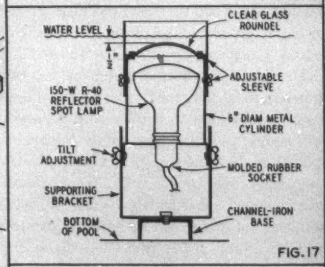


FIG. 17

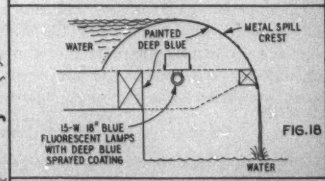


FIG. 18

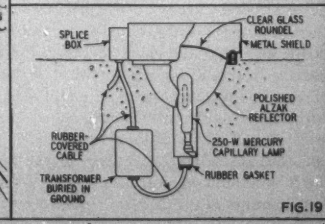


FIG. 19

row of atomizer nozzles which produce three parallel spray curtains and a supplementary layer of mist over the pool generally. As in the three main water columns, two colors—blue and gold—are provided in each line of striplights by fitting each alternate projector with a gold or blue filter. The alternate cycles of blue and gold light that progress down these strips in accordance with a prearranged sequence are synchronized with the corresponding colors in the main water columns. The two color circuits for the column lights as well as for the associated atomizer strips are connected to a special cycle-dimmer arranged to produce the effect of, first, a flow of one color, followed by a flow of the second color, then a flow of both colors combined. The effect begins with the main column lights and continues down the length of the pool with a rate of color flow of approximately ten feet per second and with alternate colors based on five-second intervals. The control device used is a brush-type flasher operating in combination with a motor-driven bank of variable autotransformers. These control the intensity as well as the switching of the separate color circuits, which are brought out at ten-foot intervals to groups of the striplights.

Along both sides of the center pool of the esplanade group and across the head of the pool at the base of the George Washington statue are vertical water jets projected to a height of about eight feet above the surface of the reflecting pools (plate II; figure 13). Each of these jets is individually lighted from beneath the water surface by a single 150-watt reflector lamp (figure 17). Across the head of the pool at the base of the Washington statue is a cascade electrically illuminated from behind (figures 13, 18). A similar back-lighted cascade heads the next pool of the group. The third pool, nearest the Lagoon of Nations, has no lighting features of itself, but serves rather as a reflecting pool in which the fountain display and the Court of Peace searchlight-canopy are mirrored (plate III).

The two plazas of the Mall—George Washington and the Four Freedoms—are lighted by means of special stanchions (figures 13, 14) topped by lighting units fitted with optical systems which project light down to the surfaces of the roadway and walkway, eliminating dispersion.

Lagoon of Nations Display

Dominant and popular lighting spectacle of the Fair, the Lagoon of Nations combines the elements of water, light, sound, flame, and fireworks in one mammoth display. Regardless of weather the evening performances of this "show" (plates I, VIII) regularly have packed thousands of Fair visitors into every available vantage point from which the spectacle could be viewed. Centrally located in the main exhibit area, the Lagoon forms a pivotal focus of interest, by day as well as by night, flanked to the west by Constitution Mall leading to the Theme Center, and to the east by the Court of Peace with its phalanx of government buildings (figure 1).

The Lagoon is an elliptical pool some 800 feet long and 400 feet wide. This area, approximately five acres, originally was a slough over which a supporting mat covered by a coating of gravel had to be laid. At the center of the pool is a wooden platform 400 feet long and 200 feet wide, mounted on piling and normally about two feet under water. This submerged platform supports the array of piping, wiring, and equipment required by the fountain itself and also supports four cylindrical kiosks 24 feet in diameter and 7 feet high which house groups of sound projectors as well as miscellaneous electric and hydraulic-valve control equipment. The plan view (figure 27) shows the "three ring" arrangement of the fountain and indicates the general arrangement of more than 1,400 water-jet nozzles, 133 gas-flame nozzles, 285 fireworks mortars, and 552 special light boxes.

At the center of each of the three circular sections of the fountain is a group of nozzles capable of projecting a column of water 150 feet into the air. Equally spaced around the concentric rings of each section are nozzles capable of projecting water jets to a height of 75 feet. Each of these 552 heavy-duty nozzles has its own twin-unit projector box for light and color effects (figures 27, 28). Miscellaneous other nozzles provide for a wide variety of water configurations. A border of graceful shape is provided around the triple operating center of the fountain by approximately 1,100 feet of strip lighting which illuminates a spray screen produced by atomizer nozzles (figures 27, 28).

PLANNING AND ARRANGEMENT

The physical arrangement and relationship of these various elements were determined through the medium of extensive studies of small-scale working models, and of experimental equipment both in miniature and full size. In the experiments with full-scale working models, several important observations were made which had a direct influence on the design of the lighting and control equipment. For example, it was found that the effect of mercury-vapor lighting of the tall water jets was especially desirable, not alone because of the rich and intense blues, greens, and other cool shades thus obtainable, but also because of the scintillating and animated "sparkle" imparted to the myriad particles of water by the stroboscopic effects of the mercury light. Also, many interesting and hitherto unobtainable shades of colors were found to be attainable by combining certain of the colors derived from the mercury lamp with other colors derived from the incandescent light sources.

Probably one of the most significant experimental observations was the extent to which color values obtained from incandescent sources were enriched by direct color-filtering of the lamp with its filaments burning at maximum temperature, as compared with color effects produced by blending the primary filtered colors from incandescent sources with conventional dimmer-control and consequent subnormal filament temperatures.

TWIN-PROJECTOR LIGHTING UNITS

The necessity for color control of the mercury light sources led to the development of an effective mechanical color-shifting and dimming device, which, as just intimated, also lends itself effectively to color control and dimming of incandescent light sources. Thus, to provide the range and combination of colors that make the foun-

tain display famous, a special semisubmersible twin-projector lighting unit was developed. Each of these units (figures 21, 22) utilizes a 1,500-watt concentrated-filament incandescent lamp and a 400-watt mercury capillary lamp. Each light source in each unit is fitted with a suitable reflector. Around each reflector is a specially devised six-sided revolving color drum, the sides of which support natural-colored glass filters, open frames, or blank metal sheets, in selected sequence. (The trade term "natural-colored" refers to color throughout the thickness of the filter glass, as compared with surface treatment.) These color drums enable effective mechanical dimming of the incandescent light as well as of the mercury light, and permit not only combinations of various colors of the two sources, but also the use of any of the several colors or tints from either of the two sources independently of the other. The complete twin unit, including incandescent lamp, mercury lamp, and all associated driving and control equipment, is mounted in a waterproof sheet-metal tank approximately 28 inches long, 28 wide, and 27 deep.

Each color drum is separately driven by a three-phase 208-volt $^1/_{75}$-horsepower 1,800-rpm synchronous motor at a speed of one revolution per minute. This speed requires a ten-second interval to pass from one color into another, or into black-out, and was determined by test and experiment to be the most desirable for smooth blending.

The problem of keeping several drums operating in multiple and with color filters always in the same relative positions was solved by a magnetic braking system that brings all drums on any circuit to a quick stop—actually within $1^1/_2$ revolutions of the motor shaft. The power for braking is supplied by a separate 60-volt d-c source, and the motor circuit is so arranged that whenever motors are disconnected from their a-c power source, two phases of the motor instantly and automatically are short-circuited and connected to one side of the d-c circuit, the other side of the d-c braking circuit being at all times common with the third a-c phase wire. In addition to the d-c braking feature, all color drums on any circuit are arranged to be resynchronized automatically at the black-out position of the color drum. This feature requires the use of a small relay, together with a cam and limit switch for each motor.

The colors and their relative positions as actually selected for the mercury projector of each twin unit are: clear, light blue, dark blue, black-out plate, "surprise" pink, and black-out plate. For the incandescent source they are: clear, yellow, blue-green, black-out plate, red, orange. The 1,500-watt screen-grid incandescent lamp has a rated efficiency of about 25 lumens per watt, or a total output of 37,500 lumens. The 400-watt mercury capillary lamp has a rated efficiency of about 45 lumens per watt, or a total output of about 18,000 lumens. Because actual tests indicated as much as 65 per cent light absorption for a one-inch depth of the brackish water available for use in the Lagoon, underwater placement of the twin lighting units was abandoned, and each unit so placed as to project approximately six inches above normal water line. Thus the glass covers of these twin units are subjected not only to the battering of the heavy deluge of falling water, but also to severe heat stresses, particularly over the incandescent unit. The narrow-beam reflectors so concentrate and localize the light beam that temperatures as high as 425 degrees Fahrenheit have been measured on the surface of the glass covers of the boxes directly above the incandescent lamps. A solution to this problem finally was achieved through the use of specially tempered plate-glass panels having exceptionally high transmission efficiency for the infrared rays. Standard heat-treated glass was found to be satisfactory above the mercury lamps.

To produce a mist or "curtain" effect around the base of the entire fountain display, there is a continuous row of atomizing nozzles. Illumination of this mist curtain is accomplished by continuous strip lighting. These strips are made up with receptacles spaced six inches on center to accommodate some 1,800 of the new 100-watt *R*-40 reflector-type lamps divided into four color groups—clear, amber, green, and red. Each reflector lamp is set in a separate adjustable cylindrical sheet-metal housing (figure 23) and provided with a natural-colored glass roundel.

FOUNTAIN CONTROLS

All elements of the Lagoon display—water, light, sound, flame, and fireworks—are remotely controlled from bench-type switchboards in a control room atop one of the government buildings overlooking the Lagoon (figures 24, 25). Water valves are selectively operated from small pilot switches which energize solenoid valves in the kiosks; these valves in turn admit city water to large hydraulically operated valves at the nozzles (figure 25). Water nozzles and associated twin-unit light projectors are placed to enable the formation of a variety of fountain patterns.

Control of the twin-light projectors is accomplished through contactor panels in the kiosks that in turn are operated from the control room. Lighting controls correspond to the water controls, so that groups of lights may be operated selectively with their associated water nozzles in a wide variety of patterns. In all, there are 19 main lighting-group controls (figure 24). Color control of these projectors is accomplished through close and accurate control of the synchronous motors driving the color drums.

The different switches on the panels in the control room permit independent operation of either mercury or incandescent color drums, facilitating ready combination of a wide variety of color tones. The grouping of a number of drums on one color switch (as many as 63 per switch) reduces to 19 the number of pairs of color-selection controls actually required for the 552 twin units on the Lagoon platform. An ingenious circuit arrangement permits the drum-control switches to be preset to any color, and then operated either individually or from master switches at the desired moment. An outstanding result of this method of color control is the subtle, almost imperceptible, transition from one color to another—an effect aided materially by the previously mentioned experimental selection of the optimum (ten-second) interval for a color translation.

Plate I (facing page). Constitution Mall, scenic backbone of the exhibit area, presents a picture of rare beauty at night. This view, looking east from high in the Trylon during the evening fountain show in the Lagoon of Nations, shows how the various effects are combined into one spectacular display; note also subdued illumination near the Theme Plaza (foreground) Courtesy Westinghouse

Courtesy Westinghouse

Plate II. Fluorescent trees themselves serve as the source of soft, evenly distributed illumination for the broad promenades along either side of Constitution Mall as well as around the Theme Plaza (figures 13, 19). Small illuminated jets frame the central reflecting pools (figures 13, 17)

Plate III. Pencil-like searchlight beams etch the night sky forming a canopy over the Court of Peace. Typical of plaza areas, the court is illuminated only by light from adjacent building façades, supplemented by a peripheral row of decorative street lights (C, figure 68)

Courtesy Westinghouse

Courtesy Westinghouse

Plate IV. Unprecedented in magnitude was the problem of evenly illuminating the three-acre exterior of the Perisphere. Special projectors mounted on adjacent rooftops provide any of three colors (amber, red, or blue) and project clouds drifting realistically across its surface (figures 2–5)

Plate V. The 800-foot Lagoon of Nations, Constitution Mall, and the Theme Center dominate this view looking west from the roof of the Federal Building which encompasses a large portion of the exhibit area. Brightly lighted pylons and other accents add sparkle to the scene

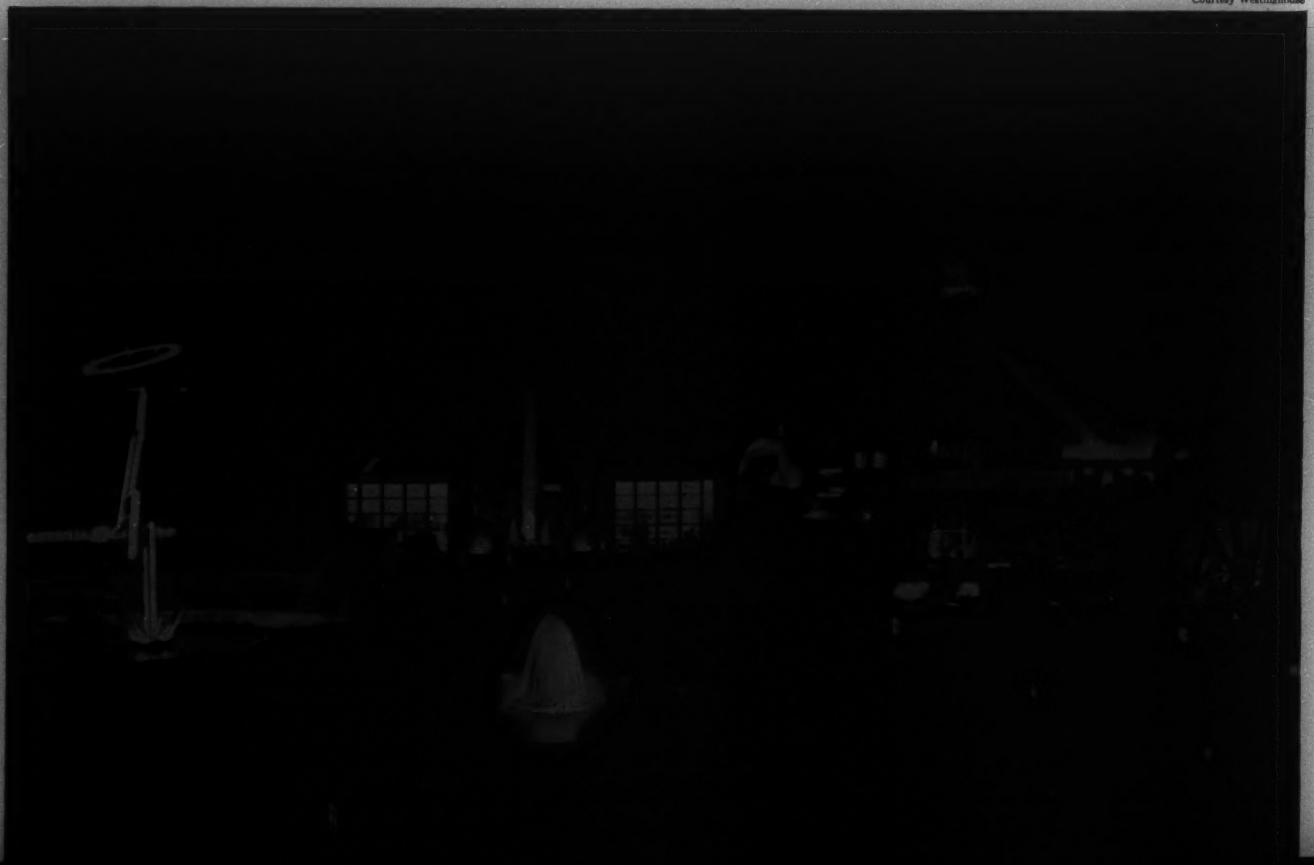
Courtesy, Westinghouse

Courtesy Westinghouse

Plate VI. Decorative pylons representing man's first-known elements (earth, fire, water, air) form the southern terminus of the Court of Power (figures 37, 39). Floodlighted building façades constitute the principal source of illumination for streets and walkways

Plate VII. Clustered around the Plaza of Light south of the Court of Power are several electrical-industries exhibit buildings. The small fountain in the foreground illustrates how centers of interest are provided in small plazas and courts throughout the grounds

Courtesy Westinghouse



Corresponding to the 19 main lighting-group controls already mentioned, there are 19 panels in the central control board (figure 24). One of the dials on each panel controls the mercury units, and the other controls the incandescent units, throughout the corresponding group of twin-projector units associated with that panel. Each control dial is so arranged that it may be rotated in either a forward or a reverse direction to any preselected color position. The arrangement of circuits and associated relay and other equipment is such that the associated group of color drums will rotate correspondingly to the selected color position. At the same time, the motor-driven pointer on the control panel immediately behind each dial accurately follows and at all times shows the position of the associated color drums. This motor-driven indicator is a duplicate of the motor, limit switch, and cam arrangement that is associated with each color drum inside the twin units on the fountain platform, and the circuits provide identical d-c braking and synchronizing control.

Control of the striplights for the border curtain of illuminated mist is accomplished through the medium of motor-driven variable autotransformers located in the kiosks, but operated from the central electrical control board. All gas burners are electrically operated from the control room and are ignited by a small pilot flame which is kept burning, in spite of the deluge of falling water, by a 10,000-volt spark ignition system. Some 280 fireworks mortars are controlled electrically through connections to central patching-panel boards in the kiosks. A total of 50 firing positions is available at jack outlets above the mortar jacks, and jumpers permit any mortar or combination of mortars to be plugged into any firing position. A step-by-step relay energizes one after another of the firing jacks in response to the closing of the "fire" button on one of the main control panels in the control room.

In a separate pump room (figure 26) convenient to both the Lagoon and the control room are motor-driven centrifugal pumps totaling some 2,700 horsepower and capable of furnishing approximately 100,000 gallons per minute. Arranged to comprise an operating exhibit in themselves, these pumps supply the Lagoon fountains. Pumps and associated equipment lend themselves to a flexibility of control (figure 25) and a promptness of response that adds to the effectiveness of the fountain "shows."

Power for the lights and equipment located on the submerged Lagoon platform is transmitted from the main distribution board near the pump room to the kiosks by 11 700,000-circular-mil three-phase feeders. All wiring in the Lagoon consists of ordinary rubber-covered conductors, with so-called watertight insulation. All conductors, including those of control circuits, are merely laid in the water and strapped to the deck of the submerged platform without any additional protection.

FOUNTAIN OPERATION

Once each evening, just at dark, a 15-minute prearranged "show" is presented in the Lagoon, combining the various elements appropriately to render an unusual form of composition that has proved to be an ever-popular attraction (plates I, VIII). The music, played by a 42-piece band in a studio in an exhibit building, is picked up stereophonically by two microphones, relayed by wire to the control room where it is amplified and monitored, and then transmitted over two separate channels to the loud-speakers in the four kiosks on the submerged fountain deck. Each diagonally opposite pair of kiosks is served by one of these channels, thus giving a two-point stereophonic effect along both axes of the Lagoon. Each kiosk contains four high-frequency and two low-frequency speaker units, totaling 500 watts in audio output capacity. This is one of the first large stereophonic installations. The sound system has a total audio output of 2,000 watts.

Split-second synchronization of the various elements during the 15-minute nightly "shows" is accomplished with the aid of specially developed "cueing" machines, one located at the top of each of the triple-unit central control boards (figure 25) and one located in the music studio. These ingenious machines are in effect special adaptations of the machinery of curve-drawing electrical measuring instruments, with the curve-drawing elements removed. Basically, each machine consists of a synchronous-motor-driven mechanism that draws the cue sheet at 60 inches per minute under a wire marker which indicates the cue instant. Each cue sheet consists of a roll of graph paper, marked off in two-second intervals, on which are plotted against the time axis all the cues and special instructions necessary for the particular group of operators served by the particular cue machine. The several operators translate the cues into the actual operation of the various control switches, including the firing of the fireworks mortars. All "cueing" machines are started and stopped simultaneously by a master switch in the central control room. By means of this system, all operations are accomplished within a fraction of a second of the predetermined time schedule and the productions have been kept so uniform that their accuracy has become a byword.

Some of the same general type of equipment is used in Fountain Lake where a spectacular element appropriate to the amusement area is furnished by the mammoth fireworks display that follows the nightly Lagoon show. The feature of this display is its mobility. Pumps, light projectors, fireworks mortars, and all such equipment are distributed among several barges which may be shifted to provide different effects, subject to control from shore through equipment similar to that used for the Lagoon.

Court of Peace

The searchlight canopy over the Court of Peace constitutes the third and easternmost portion of the feature lighting spectacle of the Fair that begins at the Theme Center (plates I, III, V). This canopy of searchlight beams gives a third dimension to this part of the nighttime picture, producing the visual impression of a raftered or coffered ceiling over this whole 450- by 900-foot area, which is flanked on either side by the pavilions of foreign governments and dominated at its easterly terminus by the $3,000,000 United States Government Building.

Plate VIII (facing page). The nightly fountain "shows" in the Lagoon of Nations ingeniously combine the elements of water jets, light, color, flame, fireworks, and sound into one harmonious whole. Part of the spectacle are the thousands of visitors who nightly jam every vantage point for this wholly unusual and enormous display Courtesy Westinghouse

Figure 20. The maze of water nozzles, lighting units, gas burners, fireworks mortars, and associated fountain equipment in the Lagoon of Nations is strikingly illustrated in this view which shows workmen preparing some of the equipment for the winter layover

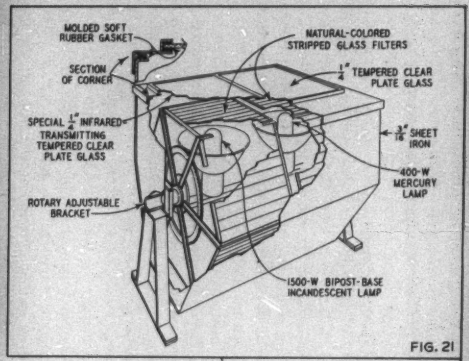

MOLDED SOFT RUBBER GASKET
SECTION OF CORNER
SPECIAL 1/4" INFRARED TRANSMITTING TEMPERED CLEAR PLATE GLASS
ROTARY ADJUSTABLE BRACKET
NATURAL-COLORED STRIPPED GLASS FILTERS
1/4" TEMPERED CLEAR PLATE GLASS
3/16" SHEET IRON
400-W MERCURY LAMP
1500-W BIPOST-BASE INCANDESCENT LAMP

FIG. 21

Figures 21, 22. Twin-unit semisubmersible projectors illuminate each main jet of the fountain. Both lamps are burned at full brilliance, color changes and dimming being accomplished by six-sided color drums with selected filters mounted in their sides, which are rotated around the lamp and reflector units

Figure 23. Some 1,800 of these reflector-lamp units illuminate the spray from the continuous row of atomizer nozzles around the outer border of the fountain (27, 28)

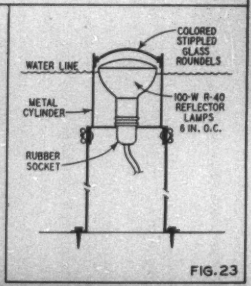


FIG. 23

Figures 24, 25. Twin control units (24) provide complete control over the twin-unit projectors (21, 22). A seperate board (25) controls the water and gas-flame jets. Co-ordinated control of the various elements of the fountain display is achieved by several synchronized cue machines (25, top)

Figure 26. A circular pump room, near one end of the Lagoon, itself a display feature with its 2,700 horsepower in 11 motor-driven centrifugal pumps, supplies a maximum of 100,000 gallons of water

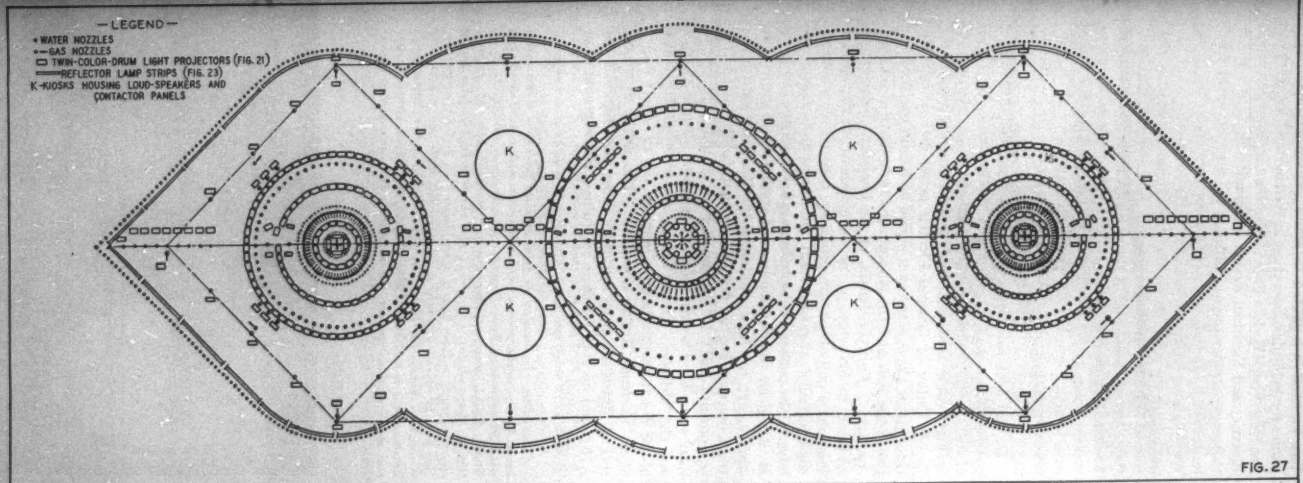


FIG. 27

Figures 27, 28. The major equipment on the 200- by 400-foot operating platform of the fountain in the Lagoon of Nations is arranged in three concentric rings (27, 28). Other equipment is so placed that various geometrical configurations may be achieved, as indicated by the dashed lines (27). The maze of equipment (20) includes 552 main water jets, each with its associated twin-unit lighting projector (21, 22), some 133 gas jets, and 285 fireworks mortars strategically arranged in eight operating groups. A continuous row of atomizer nozzles with associated lighting units (23) forms the outer border of the fountain. The total connected load for the Lagoon spectacle alone is 3,700 kw

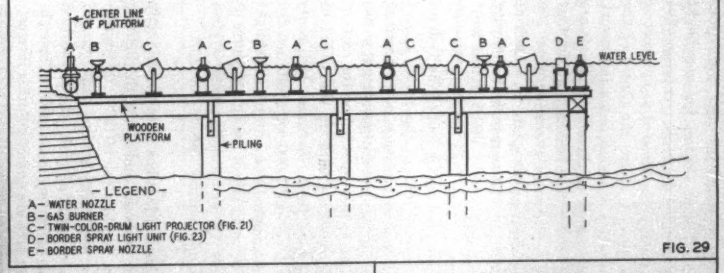

CENTER LINE OF PLATFORM
A B C A C B A C A C C B A C D E
WATER LEVEL
WOODEN PLATFORM
PILING
—LEGEND—
A—WATER NOZZLE
B—GAS BURNER
C—TWIN-COLOR-DRUM LIGHT PROJECTOR (FIG. 21)
D—BORDER SPRAY LIGHT UNIT (FIG. 23)
E—BORDER SPRAY NOZZLE

FIG. 29

Figure 29. This sectional elevation along the radius of one of the three operating circles of the fountain shows the relative placement of major equipment on the Lagoon deck and approximate operating water level

Figure 30. Seven of these illuminated "megaphone" water nozzles at about 50-foot intervals around each end of the Lagoon surrounding the fountain provide animation in these areas

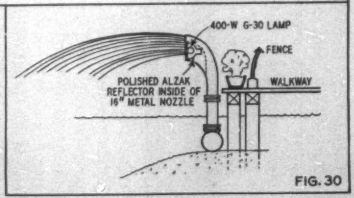


FIG. 30

Oriented and designed to climax the vista down Constitution Mall from the Theme Center, the searchlight canopy is keyed to a pyramidal structure comprising five main searchlight beams which are directed to intersect at a point some 400 feet directly above the center of the Lagoon of Nations and which form an outer framework for the fountain display. Four of these searchlights are mounted on the tops of convenient buildings at the four points of the compass at distances averaging some 700 feet from the center of the Lagoon (plate I). Each of these four units is a 36-inch 125-ampere high-intensity automatic-feed carbon-arc projector. The fifth and most powerful searchlight beam comes from a similar 60-inch army-type searchlight mounted on the roof of the Federal Building exactly on a continuation of the center axis of the Mall. Intersecting this latter "ridge pole" beam of the canopy of light structure are two groups of eight parallel pencils of light from projectors mounted on the roofs of the foreign-government pavilions flanking the Court of Peace (plate III). Each of these 16 beams has as its source one of the newly developed 1,000-watt water-cooled mercury capillary lamps mounted in a suitable searchlight housing (figure 31). The small size of the actual source of this light (approximately 1.5 by 25 millimeters) is ideal for the purpose, producing a narrow "pencil" of light.

WITHIN the limits of this article it has been possible only to outline the plan and purposes underlying the lighting scheme of the New York World's Fair of 1939; to describe in some detail the most prominent lighting displays, and show how they have been accomplished; and to mention the significant new forms of lighting developed. Throughout the enormous exhibit area are numerous other interesting and novel lighting creations, unmentioned only because of space limitations. Most of the significant basic forms of lighting, however, are represented among the various illustrations and application sketches, although, of course, many different variations, combinations, and adaptations were used by different exhibitors, all of whom made effective use of new and attractive lighting arrangements.

A World's Fair, by its very nature, offers exceptional opportunities for the presentation of new ideas. The keynote of the New York World's Fair is "better living in the world of tomorrow." Especially in the field of illumination has this keynote successfully and significantly been carried out. The Fair served as a stimulant to creative minds seeking departures from the conventional; also as a proving ground for new and better light sources, for improved methods, systems, and techniques. Its success is evidenced by such developments as the rapid commercial acceptance of the low-voltage fluorescent lamp, and the increased consciousness of lighting as an element of architectural design, a foretaste of the practices of tomorrow.

THE AUTHOR is indebted to many individuals and companies for helpful co-operation in the course of his work at the New York World's Fair. The Westinghouse, General Electric, and Eastman Kodak companies all went out of their way to place their facilities at the disposal of the Fair for carrying through many of the new developments. The Westinghouse company's Lighting Division gave every assistance in the final design and manufacture of most of the special lighting equipment used in the Lagoon of Nations, the Court of Peace, and at the Theme Center; the General Electric Company expedited the development of the low-voltage fluorescent tubes and related equipment; the Eastman Kodak Company designed and manufactured the significant new motion-picture projector for the Theme Building.

Special acknowledgment for valued and comprehensive co-operation is made to Edward H. Sniffin and H. M. Hays of the Westinghouse company; also to W. F. White and Irving Yost of that company for their untiring assistance. C. M. Cutler of General Electric acted very effectively throughout the construction period as liaison engineer between the Fair and the laboratories and plants of his own company. Fordyce Tuttle, of the Eastman company, in addition to his work in the development of the special Perisphere motion-picture projector, contributed much to the solution of other important optical and projection problems. The author's indebtedness is acknowledged to John H. Kliegl for the development of special-effect projection equipment; to Daniel Rollins of the Ward-Leonard Electric Company for the design and manufacture of control equipment; to D. D. Gillespie for the manufacture of the intricate control boards for the Lagoon of Nations display and the Perisphere Theme Show; also to A. B. McKenna of the Westinghouse Lamp Company and to Albert Fuller of the Eastman Kodak Company. The author expresses special appreciation to Editor G. Ross Henninger of the AIEE and his staff for their helpfulness in the preparation of this article.

Editor's Note: Incidental to the preparation and publication of this article, persons and organizations too numerous to mention have made valuable contributions which are acknowledged hereby. Special credits are due as follows: To P. L. Giering, J. G. Lawrence, and other members of the World's Fair staff, especially Wm. W. Morris who carried his camera 300 feet up into the Trylon to secure the view shown on plate I; to Harry Flowers, of the Flowers Photo Engraving Corporation, New York, for valuable assistance in the preparation of the color plates; to the Westinghouse company for making these plates available for use in ELECTRICAL ENGINEERING; *to the General Electric Company, the General Motors Corporation, the Westinghouse company, and the World's Fair Corporation for various illustrations.*

Figure 31. The 16 pencil-like searchlight beams forming a canopy over the Court of Peace (plate III) have as their source the newly developed 1,000-watt water-cooled mercury capillary lamp. One of the searchlights with associated control equipment is shown here

This lamp operates at 840 volts and produces some 65,000 lumens, an equivalent brightness of about 300 candle power per square millimeter, which is about one-fifth the brightness of the sun. About three quarts of cooling water per minute is required for each lamp

Some Pylons

FIG. 32

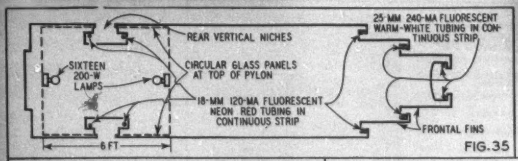
FIG. 34

Decorative pylons, strikingly illuminated at night, provide sharp accents that contribute sparkle to the nighttime scene, at the same time serving as points of orientation for New York World's Fair visitors

Figures 34, 35. Two pairs of 66-foot pylons at the west entrances are brightly outlined at night by high-voltage fluorescent tubing hidden in reflecting coves (35). The circular panels at the top are illuminated by incandescent lamps

FIG. 36

Figure 36. The serpentine tracery of these 145-foot "hairpin" pylons is provided by exposed pink and green high-voltage fluorescent tubing


REAR VERTICAL NICHES
SIXTEEN 200-W LAMPS
CIRCULAR GLASS PANELS AT TOP OF PYLON
18-MM 120-MA FLUORESCENT NEON RED TUBING IN CONTINUOUS STRIP
25-MM 240-MA FLUORESCENT WARM-WHITE TUBING IN CONTINUOUS STRIP
FRONTAL FINS
8 FT
FIG. 35

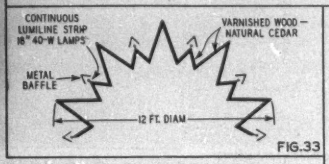


FIG. 33

Figures 32, 33. An effective illusion of translucence is given to the varnished natural cedar surface of the 115-foot Star Pylon by continuous Lumiline strips hidden behind reflecting troughs

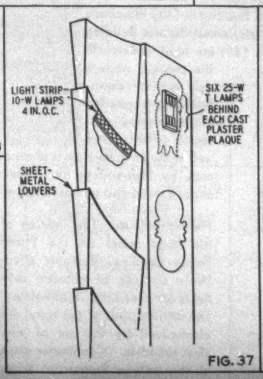
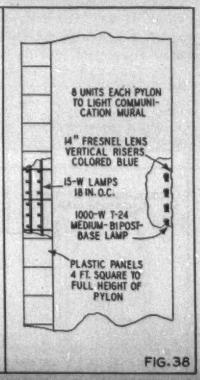


FIG. 37


8 UNITS EACH PYLON TO LIGHT COMMUNICATION MURAL
14" FRESNEL LENS VERTICAL RISERS COLORED BLUE
15-W LAMPS 18 IN. O.C.
1000-W T-24 MEDIUM-BIPOST-BASE LAMP
PLASTIC PANELS 4 FT. SQUARE TO FULL HEIGHT OF PYLON
FIG. 38

Figures 37–40. At opposite sides of the Theme Center: Four 55-foot louvered pylons (37, 39) representing earth, air, water, and fire, man's first-known elements, mark the southern terminus of the Court of Power; two 116-foot pylons stand in front of the building at the north end of the Court of Communications (38, 40). Incandescent projectors in the backs of the latter illuminate the mural

Typical Exteriors

IN general the design of each Fair exhibit building provides a single dominating architectural element such as the spiral pylon on the Operations Building (figure 48). These elements serve to individualize the buildings and in most instances are the primary source of "sparkle" lighting for the structure itself. Thus the lighting treatment for individual buildings is developed to meet the special needs of those buildings, as in all decorative pylons (figures 32–40), and utilizes a wide variety of light sources including high- and low-voltage fluorescent tubing, much of which is used exposed (figures 45, 53). In some instances where a particular translucent effect is desired, tubing of different colors is concealed as in the fin of the Chemicals and Plastics Building (figures 41, 44). The façades of the structures in general are treated

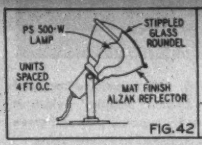


FIG. 42

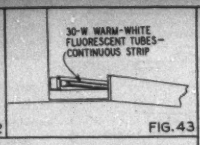


FIG. 43

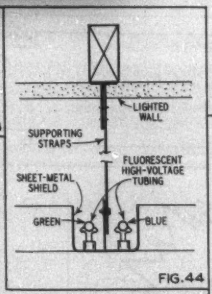


FIG. 44

Figures 41–44. Conventional floodlights (42) illuminate the upper facade of the Chemicals and Plastics Building (41). Fluorescent cove lights (43) are used underneath the canopy, while a new type of downlight (59) is installed in the canopy ceiling. The plaster wall of the fin at the right is given a translucent appearance by high-voltage fluorescent tubing concealed under a metal grid set out from the wall (44)

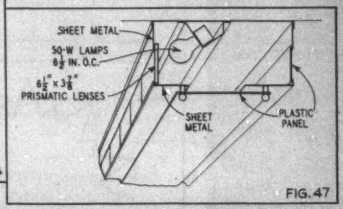
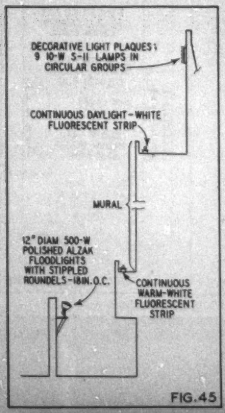


FIG. 47

Figure 47. Details of lighting strip under entrance portico of Operations Building (48)


DECORATIVE LIGHT PLAQUES: 9 10-W S-11 LAMPS IN CIRCULAR GROUPS
CONTINUOUS DAYLIGHT-WHITE FLUORESCENT STRIP
MURAL
12" DIAM 500-W POLISHED ALZAK FLOODLIGHTS WITH STIPPLED ROUNDELS—18IN. O.C.
CONTINUOUS WARM-WHITE FLUORESCENT STRIP
FIG. 45

Figures 45, 46. The lighting of the huge mural on the North Foods Building illustrates effectively the use of reflector strip lights combined with floodlighting. The brilliant reds of the mural are emphasized by the use of pink glass roundels. Continuous strips of low-voltage fluorescent tubes illuminate the setbacks, and the top is crowned by a ring of circular nine-lamp plaques. Triple zigzag strips of fluorescent neon tubing encircle the building near the top, except for the area shown

FIG. 46

Figure 48. The spiral pylon of the Operations Building is composed of 12-inch 40-watt T-8 lamps on four-inch centers mounted in a spiral trough supported by a central pipe. The facade at the left is lighted by blue fluorescent tubes in fluted coves. A decorative strip (47) underneath the portico illuminates mural and walkway

with built-in lighting units; these serve to illuminate the painted wall murals which in turn reflect soft diffused light to adjacent walkways. The colors of light sources are selected to accentuate the colors of the murals or façades, and in some instances additional color filters are applied. The use of plaques, as on the Hall of Communications (figures 50, 51), provides many possibilities for accent color lighting applicable to both decorative and utilitarian purposes. On this and the facing page are presented selected night views showing typical exterior lighting. Space limitations obviously permit illustrating only a few typical applications of the significant types of exterior illumination at the Fair.

Figure 49. Back-lighted sculptures and blue and white fluorescent tubes behind a glass-brick wall provide decorative elements and unobtrusive walkway illumination near the Theme Center where special precautions are taken to avoid diluting the Perisphere illumination. The figures are approximately 18 feet high

Figures 50, 51. Back-lighted plaster plaques provide general illumination and decoration along the west wall of the Hall of Communications. Other plaques of different design serve a similar purpose along the east wall

Figure 52. At the entrance to the Shelter Building are two rows of 150-watt units with prismatic lenses; the inner row is directed toward the mural, difficult to light because of its specular surface, and the outer row downward

Figure 53. Exposed fluorescent tubing illuminates this typical information booth

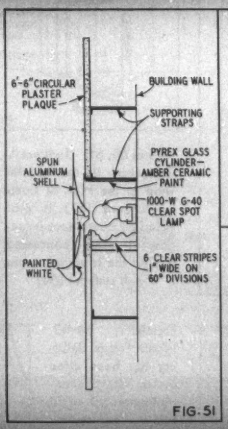


FIG. 51

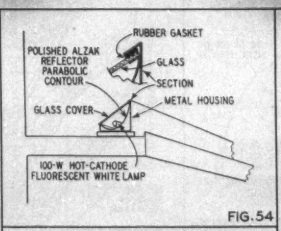


FIG. 54

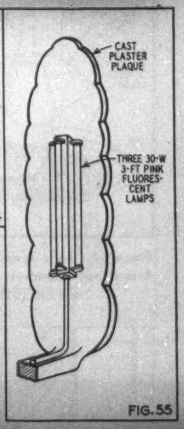


FIG. 55

Figures 54–56. Floodlights employing the new hot-cathode fluorescent lamp preserve the natural beauty of the blue, green, and white murals (54, 56) along the east side of the Court of Power. Decorative plaques between murals are back-lighted by groups of fluorescent tubes (55, 56). Note flower-like street lights (1, 68)

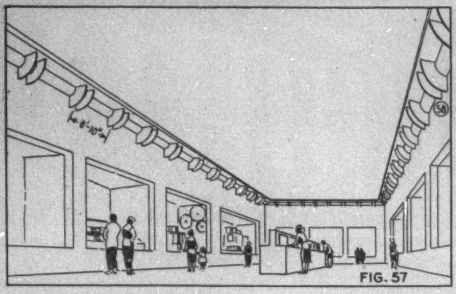


FIG. 57

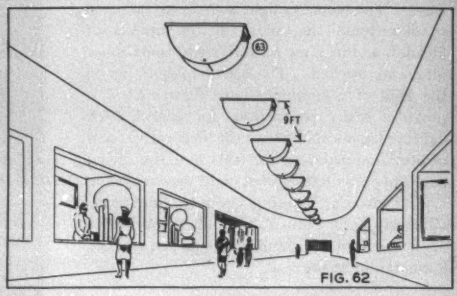


FIG. 62

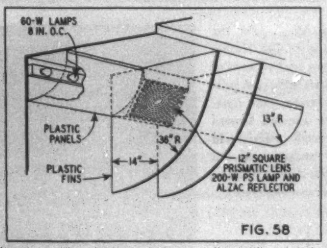


FIG. 58

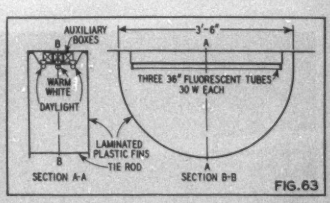


FIG. 63

Figures 57, 58; 62, 63. The main exhibit hall of the Chemicals and Plastics Building appropriately utilizes plastic panels and fins, combined with prismatic lenses, in a decorative strip extending all around the outer edge of the ceiling (57); incandescent lamps in strips and in reflectors provide the illumination (58). The exhibit wing of this building (62) is illuminated by a central row of units using low-voltage fluorescent tubes and semicircular plastic fins (63). The use of new light sources and new materials is typical of general illumination applications throughout the Fair

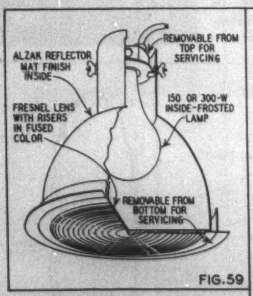

ALZAK REFLECTOR MAT FINISH INSIDE
REMOVABLE FROM TOP FOR SERVICING
FRESNEL LENS WITH RISERS IN FUSED COLOR
150 OR 300-W INSIDE-FROSTED LAMP
REMOVABLE FROM BOTTOM FOR SERVICING
FIG. 59

Figure 59. New downlight ceiling fixture used extensively throughout the Fair (61)

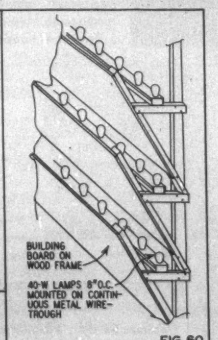


FIG. 60

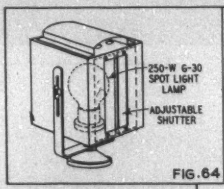


FIG. 64

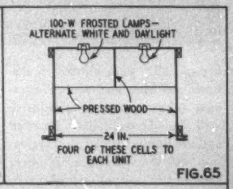


FIG. 65

Figures 60, 61. Indirect illumination in this exhibit wing of the Hall of Communications (61) is provided by continuous incandescent strips concealed behind the louvered upper wall surfaces (60)

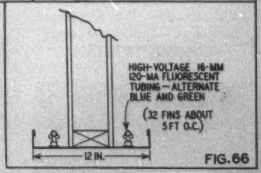


FIG. 66

FIG. 61

Figures 64–67. North Foods Building has been cited for its effective coordination of light and architecture (67); 32 projectors (64) hidden above the ceiling plaque throw light beams toward the huge fins, which are lighted by fluorescent tubing (66). Ceiling wells (65) illuminate the exhibit wing

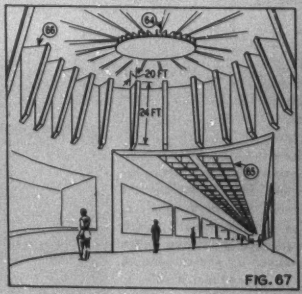
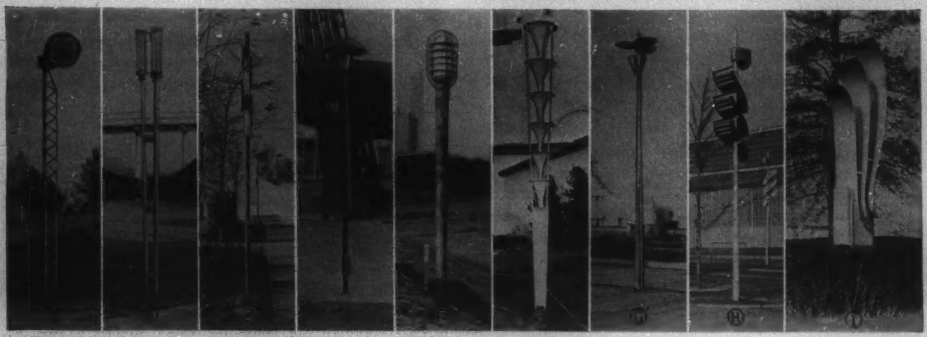


FIG. 67

Typical Street Lights



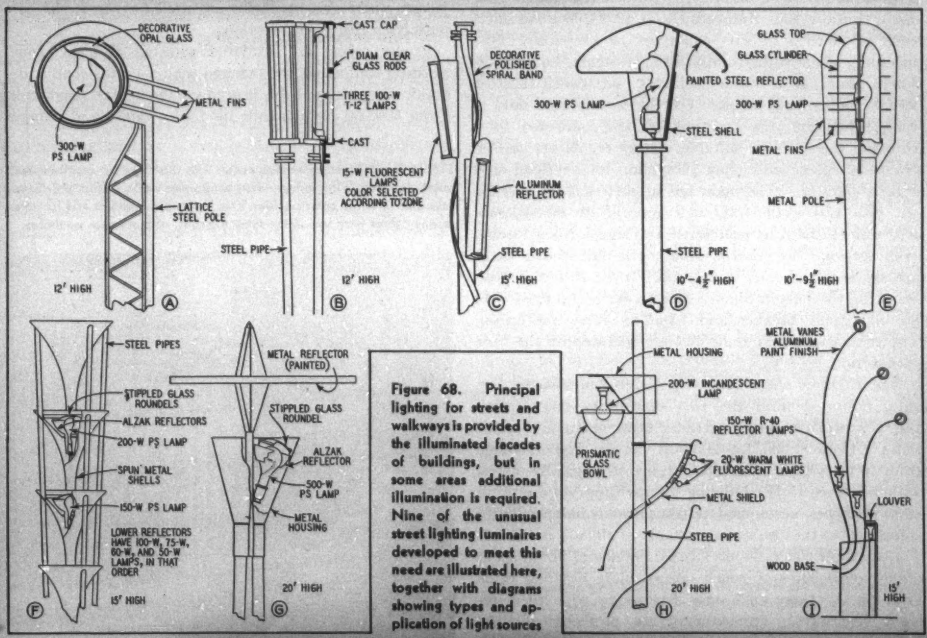


Figure 68. Principal lighting for streets and walkways is provided by the illuminated facades of buildings, but in some areas additional illumination is required. Nine of the unusual street lighting luminaires developed to meet this need are illustrated here, together with diagrams showing types and application of light sources

Figure 69. This fountain in Bowling Green plaza, which utilizes back - lighted glass blocks topped by a gas flame, effectively illustrates the general treatment of small courts and plazas throughout the Fair grounds by providing so-called "accents" in these areas

Power-Supply and Public-Address Systems at the New York Fair

P. L. GIERING
MEMBER AIEE

JOHN G. LAWRENCE
NONMEMBER AIEE

An 80,000-kva electric distribution system supplies the Fair's light and power loads; an extensive public-address system broadcasts programs and announcements throughout the Fair grounds.

TO SUPPLY the light and power load at the New York World's Fair two 40,000-kva 27/4-kv substations and some 278 4,000/120–208-volt primary service centers are provided. To prevent a service failure involving either substation from crippling operations too seriously, independent radial distribution systems from each of the substations pretty well blanket the entire Fair grounds, with the total load of any one area pretty well divided between the two. This is probably the largest application to date of nonmetallic-sheathed cable on 4,000-volt service.

Carrying out the idea of segregation, the two main substations are situated on opposite sides of the exhibit area. Each contains four transformers of 10,000-kva capacity, each of which is directly connected to a separate 27-kv incoming feeder without intervening switching equipment. Each feeder is a three-conductor 500,000-circular-mil 29-kv lead-covered cable. On the low-voltage side, in each substation, the transformers are connected to a common bus through suitable voltage regulators and oil circuit breakers with relay protection for overload and reverse current. The main bus in each station may be cut into two sections through appropriate oil switches with differential relay protection, two transformers feeding each section. In general, from each bus section there are six feeder circuits and a spare (total 28 feeder positions for the two stations); each feeder is equipped with an oil circuit breaker and overload relay protection. The substations were built and are operated by the Fair corporation.

The 25 three-phase four-wire underground feeder circuits radiating from the two substations and serving the 278 primary service centers total about 50 circuit miles. These 4,000/120–208-volt service centers range from 10 to 2,000 kva in capacity, are strategically placed with reference to the building groups they serve and, in most instances, accommodate transformers independently connected to the two radial systems as already indicated. Transformers generally are located outside of buildings in roofless enclosures of which one or more building walls form parts; these enclosures harmonize with their related structures. Transformers are protected on the substation side by boric-acid fuses, of 25,000- or 40,000-ampere capacity depending upon the distance from the supply substation.

All buildings erected by the Fair corporation and all the larger exhibit buildings are served by two feeders, one from each substation, with the lighting load divided between them. Certain exhibit buildings fed from only one circuit, have storage batteries of ample capacity for emergency lighting. The 120–208-volt circuits inside the buildings are carried on racks in the attics adjacent to catwalks, from which the branch-circuit panels are also accessible. An overlap of illumination circuits is provided in all parts of the grounds to prevent complete darkness of any area in case of a substation failure. No provision is made at service centers for transfer of load from one distribution feeder to another.

Four-inch precast concrete feeder ducts are laid directly in the ground without any supporting mats. Similarly, precast concrete manholes are used. Separate, but adjacent, ducts and manholes are used for the feeder systems from the two substations.

Feeder cables are insulated with an oil-base ozone-resisting compound and covered with asbestos conducting braid; bare copper cable is used for the neutral conductor. From 500,000 circular mils for feeder cables and number

(Top) Typical primary service center with dual feeders, one from each substation, supplying independent transformer banks. (Bottom) Separate duct lines for power cables from the two substations and for telephone cables were laid in the same trenches, with separate manholes

P. L. GIERING is chief electrical engineer and JOHN G. LAWRENCE is superintendent of displays, New York World's Fair 1940 Inc.

4/0 for neutral, the sizes are diminished respectively to number 4/0 and number 2 toward the ends of the circuits where the load is less. Service connections have been materially simplified and facilitated through the use of preinsulated mechanical fittings called "crabs", where the cables are joined in the manholes. Groups of street lights, concession stands, and small exhibit buildings receive power at 120 or 208 volts from convenient transformer service centers associated with the larger buildings. For these circuits rubber-insulated nonmetallic-sheathed cables are used, buried directly in the earth with a plank covering to prevent mechanical damage. Under roadways the cables are in ducts.

All power and communication circuits to and throughout the Fair grounds are underground.

PUBLIC-ADDRESS SYSTEM

From 23 loud-speaker outlets at strategic points throughout the Fair grounds, special announcements, music, and other programs are broadcast by means of an extensive public-address system. The heart of this system is the public-address center in the Hall of Communications, which is constructed as an exhibit and is visible to the public through large plate-glass windows.

The public-address center contains a studio for the pickup of orchestras, a smaller studio for the origination of talks or interviews, and two small booth-type studios for the origination of programs consisting of transcriptions, announcements, or pickups from radio receivers. An additional function of the small studios is to provide final monitoring of programs transmitted to the public-address center from various parts of the Fair grounds.

All programs clear through a large horseshoe-shaped master console which forms the centerpiece of the master control room. The functions of this console are analogous to the master control console of a well-equipped radio-broadcasting station. Five panels on the face of this console perform four major functions. The program-selection panel contains the controls and indicators of an automatic preset relay system which permits the independent switching of any of six program-channel control units on the console to any of ten input lines feeding the console. The program-control panel contains six channel-control units, each of the "bridging" type, and provides individual means for amplification, level control, level indication, and monitoring. Each of four channels feeds a high-level low-impedance bus; the remaining two channels are used to feed Fair programs to various radio stations. Two program-distribution panels provide 50 individual outlet-control panels which feed telephone lines running to the various outlets around the Fair grounds. Each outlet panel provides for: switching the outlet to any of the four busses; volume control; monitoring connection; and remote switching of the a-c power at the loud-speaker outlet amplifier, which is accomplished by direct current over a telephone line. Completing the master control console is an order-wire panel which contains all equipment for the control and operation of six incoming telephone lines used for communication during remote pickups.

In general, each outlet consists of an amplifying system to bring the program up to the desired output level, and a loud-speaker system capable of handling that output. For the most part, the amplifiers are standard commercial units capable of an audio output of 50 watts each. Whenever necessary to supply more than 50 watts to a speaker system, two or more amplifier units are used in multiple.

Except for the Perisphere outlet, only three types of loud speakers are used throughout the grounds:

Type A. Self-contained two-way speaker system utilizing theater-type high- and low-frequency units. Speakers are housed in a weatherproof 36-inch cube and have an audio output of 50 watts.

Type B. Eighteen-inch permanent-magnet speakers with waterproof diaphragms; audio output 25 watts. These units either use the surrounding wall surfaces for baffle area or are mounted in 56-inch spun aluminum bidirectional baffles.

Type C. Metal weatherproof exponential horn driven by a unit having a plastic diaphragm; audio output 100 watts (used in only one location).

In general, all speakers are concealed either by building them into existing wall surfaces and facing with inconspicuous grills, or by modeling them into specially designed towers.

The Perisphere unit is perhaps the most interesting of the 23 outlets. Here the under surface of the Perisphere and the surface of the pool of water beneath it are utilized as a circular "horn" of approximately exponential form capable of distributing sound around a 360-degree angle. The driving equipment is installed in a pit 22 feet in diameter and 12 feet deep below the exact center of the sphere; it comprises 24 low-frequency and 12 high-frequency units. An amplifying system having an audio output of 720 watts is used to drive the 36 speakers. The extraordinary low-frequency characteristics of this system permit a sound pressure level of $2^1/_2$ bars to be effected at the edge of the pool at a frequency of 20 cycles, which is said to establish this "horn" as the most powerful low-frequency reproducer ever constructed. Since the curb of the loudspeaker pit is only six inches above the water level of the pool, and no mechanical connection exists between the pit and the Perisphere, the system does not in any way mar the architectural lines of the structure.

All Fair programs, whether broadcast throughout the grounds from the 23 loud-speaker outlets or transmitted to radio stations for radiobroadcasting purposes, clear through this master control console at the public-address center in the Hall of Communications

Of Current Interest

From AEC . . .

ITEMS appearing under this heading are from the news service of American Engineering Council.

SEC Moves to Enforce Holding Company Ban

Nine of the largest public-utility holding companies in the country, with assets totaling nearly $9,000,000,000, have been served by the Securities and Exchange Commission with orders directing each of them to submit plans for complying with the so-called "death sentence" provisions of the Public Utility Holding Company Act of 1935, designed to eliminate complicated intercorporate relationships. The companies concerned are: Electric Bond and Share Company, Engineers Public Service Company, Middle West Corporation, United Gas Improvement Company, Cities Service Power and Light Company, North American Company, United Light and Power Company, Standard Power and Light Corporation, Commonwealth and Southern Corporation.

The statute permits operating utility companies to be controlled by holding companies which are, in turn, controlled by other holding companies, but forbids this process to be carried any further. (At present some systems have as many as nine layers of corporate ownership.) It also limits a holding company to one integrated public-utility system located in the same geographical area plus such additional systems as meet certain requirements, including geographical proximity.

In the law as passed the SEC was directed to bring about the necessary simplification "as soon as practicable" after January 1, 1938. Sincet his date the commission has endeavored to induce the companies to act voluntarily, with some success. But the results have been so limited that it is now taking this means of bringing about an acceleration of the process.

First formal answer to the order was made recently by the Engineers Public Service Company. While acknowledging that its properties do not meet the standards of the Public Utility Holding Company Act of 1935, the company asked the commission to dismiss the pending proceedings on the ground that the "death sentence" contained in the act is unconstitutional. It contends that compliance with the law would force it, within two years, to divest itself of large blocks of securities and other assets in what would amount to a "forced liquidation," to the detriment of its stockholders. This, it argues, would be the equivalent of taking private property without just compensation, and is therefore contrary to the Constitution. The Engineers Public Service Company controls operating electric companies in 15 states.

Simplification of another big holding-company system—Associated Gas and Electric—is now in the hands of trustees following the bankruptcy of its two top organizations, Associated Gas and Electric Corporation and Associated Gas and Electric Company. Control over the former has been vested by a Federal court in Willard L. Thorp, research director for Dun and Bradstreet and a special adviser to Secretary of Commerce Harry L. Hopkins, and Denis J. Driscoll, chairman of the Pennsylvania Public Utility Commission and a former Congressman who took a leading part in passing the Holding Company Act. Affairs of the second company are in the hands of Walter H. Pollak, attorney. These two companies filed bankruptcy petitions following an order by the SEC forbidding what it considered unjustified "upstream" payments by companies in the system.

That the SEC is considering certain relaxations in its rules in order to remove obstacles from the issuance of corporate securities was disclosed by Chairman Jerome Frank in a recent speech. Specifically mentioned was a reduction in the number of public hearings now held before approving such issues by utility companies. Present practice is to schedule hearings in all cases, many of which, it is felt, could be eliminated.

George C. Mathews, who has served as a commissioner since the formation of SEC, resigned on April 15 to become associated with the Northern States Power Company.

FCC Faces Problems

The regulation of television broadcasts for commercial purposes and the provision of channels for the Armstrong system of frequency-modulation radio stations are providing current puzzles for the Federal Communications Commission, charged by law with responsibility for maintaining order in the radio spectrum.

On February 29, FCC issued an order stating that after September 1, 1940, television stations would be permitted to charge commercial sponsors with the cost of program production, hitherto carried on experimentally. On the strength of this order the Radio Corporation of America started a selling campaign on television receiving sets at prices ranging from $200 to $600, with the intent of marketing 25,000 sets this year. Two rival companies in the television field—Philco and Dumont—protested that the sale of a large number of RCA-type receivers would tend to "freeze" the technical standards of an art still in the process of development or alternatively rapidly make these sets obsolete, to the disadvantage of their purchasers. Thereupon the FCC, on March 22, decided to reconsider its earlier order and suspended its effectiveness pending the results of public hearings that started on April 8.

Hearings on a number of pending applications for permission to construct new radio-broadcasting stations on the frequency-modulation principle began March 25. Experiments with this new type of transmission have developed a number of claimed advantages over the normal type of power-modulated broadcasting, including the elimination of static, greater fidelity, less interference between stations, and greater range for low-power transmitters. Since it requires radically different transmitters and receivers, however, it could supplant present facilities only at the expense of replacing millions of dollars' worth of equipment. Its supporters are pleading for the allocation of enough wave-bands to permit service in certain selected urban areas.

TNEC Opens Hearings on Technologic Changes

On April 8 the Temporary National Economic Committee began a new series of hearings, expected to extend over a period of some three weeks, to develop information on the broad subject of technological change and its effect upon employment and production. Invited to testify were over 40 leaders of science, industry, and organized labor in the fields of automobile manufacture, steel, coal, railroads, textiles, communications, office appliances, agriculture, and vocational and consumers' education.

In announcing the hearing Senator Joseph C. O'Mahoney, chairman of the committee, pointed out: "Without modern technology, mass production would not be possible; it is technology which has enabled industry to organize into great concentrated units of production and distribution. Technology has created many new industries and has provided many new opportunities for labor, though at the same time it has unquestionably displaced many workers. The committee plans to study seriously the impact of technology in all its implications, what it means in terms of employment, of unused capital, of the effective organization of our nation's resources."

The chairman also made it clear that the committee entered its task with no preformed judgments, and that the hearings were not intended to express support for his recently introduced bill to provide a system of rewards and contributions for the greater utilization of labor in industrial production through the taxing of machines.

Last month the TNEC completed a series of hearings on the effects of various state regulations upon interstate commerce.

Other Societies . . .

Quarter Century of Engineering Foundation. A recent report of the Engineering Foundation points out that since its establishment in 1914 the organization has carried out 73 research projects involving expenditure of more than $3,000,000. Out-

Future Meetings of Other Societies

American Association for the Advancement of Science. Summer meeting, June 17–22, 1940, Seattle, Wash.

American Physical Society. 235th meeting, June 19–20, 1940, Seattle, Wash.

236th meeting, June 20–22, 1940, Pittsburgh, Pa.

American Society for Testing Materials. 43d annual meeting, June 24–28, 1940, Atlantic City, N. J.

American Society of Civil Engineers. Annual convention, July 24–26, 1940, Denver, Colo.

American Society of Heating and Ventilating Engineers. Semiannual meeting, June 17–19, 1940, Washington, D. C.

American Society of Mechanical Engineers. Semiannual meeting, June 17–21, 1940, Milwaukee, Wis.

American Society of Refrigerating Engineers. 27th spring meeting, June 9–11, 1940, Skytop, Pa.

Edison Electric Institute. Annual meeting, June 3–6, 1940, Atlantic City, N. J.

Institute of Radio Engineers. 15th annual convention, June 27–29, 1940, Boston, Mass.

National Electrical Manufacturers Association. May 14–17, 1940, Hot Springs, Va.

Society for the Promotion of Engineering Education. 48th annual meeting, June 24–28, 1940, University of California, Berkeley, Calif.

Society of Automotive Engineers. Summer meeting, June 9–14, 1940, White Sulphur Springs, W. Va.

standing projects have included a ten-year study of alloys of iron, work of a special committee on cotton-seed processing, an arch-dam investigation, and research in the fatigue of metals. Of electrical-engineering interest are projects on welding and dielectric absorption; studies of personnel and engineering education have also been made.

Mathematics Congress Cancelled. The International Congress of Mathematicians, scheduled to be held at Cambridge, Mass., September 4–12, 1940, under the auspices of the American Mathematical Society (*EE, April '39, p. 180*) has been cancelled because of the war in Europe, it was announced recently.

Industry • • • •

Bell Laboratories Demonstrate Stereophonic Recordings

A demonstration program of stereophonic recordings of "enhanced music" was presented by Bell Telephone Laboratories, Inc., at Carnegie Hall, New York, N. Y., April 10, 1940. Recordings of orchestra, organ, and choral music, oratorio, opera, and drama were included in the program. The records are made on motion-picture film.

Stereophonic reproduction of music, first demonstrated in 1933 by Bell Laboratories in collaboration with Doctor Leopold Stokowski, then conductor of the Philadelphia Symphonic Orchestra, used three sound-projection systems to transmit not only the full volume and tonal range of the original, but also an illusion of the locations and physical space occupied by the performers. At the first demonstration music was transmitted by telephone from Philadelphia to Washington, D. C., over three specially conditioned circuits, and after amplification projected by three loudspeakers. Tone and volume of the music were modified by means of electrical controls. In 1935 a stereophonic system was used to re-enforce music presented at an open-air concert directed by Doctor Stokowski in the Hollywood Bowl, Hollywood, Calif. With the development of stereophonic recording, original recordings of stereophonically reproduced music are reviewed by the conductors, who may make desired tonal and volume changes by means of the controls, and new stereophonic records are made of the performance as thus "enhanced."

N. E. Research Day. Fostering research as a method of filling idle factories, the New England Council, regional development organization, plans to observe May 17 as "Research Day." A committee of the council is in charge of plans, with subcommittees for each of the six New England states. W. H. Timbie (A'10, F'24) professor of electrical engineering and industrial practice, Massachusetts Institute of Technology, Cambridge, heads the Massachusetts subcommittee, and H. C. Rankin (A'25, M'34) laboratory engineer, New England Power Service Company, Providence, R. I., that for Rhode Island.

Lighting Booklets. An illustrated reference booklet on lighting and wiring, entitled "Your Home" has been issued by the Western Institute of Light and Vision, as the second in its series of bulletins. Material in the booklet was compiled by F. A. Hansen (M'31) director of the organization. A revised edition of the first bulletin, "Seeing," which was published in 1939, has been issued also. Copies of the bulletins may be secured from the Western Institute of Light and Vision, 3407 Lowry Road, Los Angeles, Calif., at 25 cents per single copy, prepaid; quantity prices on request.

Education • • •

Summer Graduate Institute. Armour Institute of Technology, Chicago, Ill., is sponsoring a summer graduate institute in engineering and science, during June, July, and August, 1940. The institute, intended for engineers, industrialists, and educators, will consist of three four-week terms, and is divided into seven sections, one of which will be on electrical engineering and physics. The division into four-week terms is planned to enable employed engineers and others to carry on advanced study during their vacations. Courses will be presented by members of the Armour faculty and visiting professors.

Effective Speaking Course. The ten-week summer course in effective speaking, presented annually for ten years under the auspices of The American Society of Mechanical Engineers, will be given at the Engineering Societies Building, 29–35 West 39th Street, New York, N. Y., beginning June 27, 1940. Conducted by R. C. Scafe, the course includes the fundamentals of salesmanship and human relations. The fee is $12 for members of the engineering societies; $15 for nonmembers.

Letters to the Editor • • •

INSTITUTE members and subscribers are invited to contribute to these columns expressions of opinion dealing with published articles, technical papers, or other subjects of general professional interest. While endeavoring to publish as many letters as possible, Electrical Engineering reserves the right to publish them in whole or in part or to reject them entirely. Statements in letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the AIEE. All letters submitted for publication should be typewritten, double-spaced, not carbon copies. Any illustrations should be submitted in duplicate, one copy an inked drawing without lettering, the other lettered. Captions should be supplied for all illustrations.

Electric Distribution Systems in Buildings

To the Editor:

L. W. Moxey is to be commended for his use of Kelvin's law in connection with electric conductors in buildings, as illustrated in figures 2 and 3 of his paper "Electric Distribution Systems in Buildings," ELECTRICAL ENGINEERING, March 1940. In figure 3 he states that with an average load factor of $\frac{0.5 \times 2{,}000}{8{,}760} = 0.14$ or 14 per cent, and with energy at two cents per kilowatt-hour, it pays to use heavy conductors—that is, it pays to design them for less than the allowable temperature rise. The advantages in longer life of insulation, better voltage regulation, and possibility of future increases in connected load are obvious. A similar conclusion was reached by the writer in "Resistance Loss and Conductor Size," examples 5 and 6, *General Electric Review*, November 1938, page 484.

Of course, there are many branch circuits in buildings in which the load factor for the conductors is less than 14 per cent, and such circuits should usually be designed according to the temperature rise of the conductors or the voltage drop. On the other hand, there are circuits, such as in hallways of office buildings, where the load factor is much higher than 14 per cent, and where the use of Kelvin's law is particularly to be recommended.

The computations for Kelvin's law can be greatly simplified for practical designing. For each class of service a recommended maximum current density for copper can be computed. Then all that the designer needs to watch is to see that the current density in conductors, chosen in the usual way, does not rise above the maximum, and if it does, to specify larger conductors. The progressively lower price per pound of

conductors as the size increases is easily brought into the computations and enhances the advantage of using larger conductors.

This method of computation may be applied to single-conductor underground cables which in some favorable conditions should be rated, in order to save money, at less than their usual current rating based on temperature rise. The method is applicable also to overhead transmission lines, especially where the length is relatively short or where hollow conductors are used.

H. B. DWIGHT (A'11, F'26)

(Professor of electrical machinery, Massachusetts Institute of Technology, Cambridge)

Lighting the New York World's Fair

To the Editor:

I have just gone over the galleys of Mr. R. C. Engelken's article on the lighting of the New York World's Fair shortly to appear in ELECTRICAL ENGINEERING. I want to say that the job could not have been done without the clearheadedness and ingenuity of both Mr. Engelken and Mr. J. S. Hamel. It was a great pleasure to work with them and one of the high spots I shall never forget.

BASSETT JONES

(Consultant to the Board of Design, New York World's Fair 1939)

Computing Light Output

To the Editor:

In illumination problems, it is often necessary to compute the solid angle of a light beam in steradians in order to determine the total flux emitted by the source in lumens. When the plane angle of divergence of the beam is small and, hence, the half angle is small, the use of the common relationship $\omega = 2\pi(1 - \cos \alpha)$ becomes quite cumbersome. Slide-rule computation of the cosine term is valueless and even the use of four-place trigonometric tables may result in large errors. If, however, the cosine term is expanded in an infinite series, the following result may prove helpful.

$$\omega = 2\pi(1 - \cos \alpha)$$

$$\cos \alpha = 1 - \frac{\alpha^2}{2!} + \frac{\alpha^4}{4!} - \frac{\alpha^6}{6!} + \ldots .$$

Neglecting the terms to the right of $\frac{\alpha^2}{2!}$:

$$\omega = 2\pi\left[1 - \left(1 - \frac{\alpha^2}{2!}\right)\right]$$

$$\omega = 2\pi \times \frac{\alpha^2}{2}$$

$$\omega = \pi\alpha^2$$

ω is the solid angle in steradians subtended by a cone whose plane half angle is α in radians. This relationship is easy to apply and very accurate for total divergence angles up to 20 degrees. Slide-rule calculations are sufficiently accurate.

HERBERT G. BLUMBERG (Enrolled Student)

(University of Michigan, Ann Arbor)

Magnesium-Copper Sulphide Rectifier Battery Charger

To the Editor:

In the December 1939 issue of ELECTRICAL ENGINEERING, I noted some comments by E. A. Hartry on C. A. Kotterman's paper dealing with magnesium-copper sulphide rectifiers for railway battery charging.

To me these comments are neither pertinent to the type of application discussed by Mr. Kotterman, nor correct in their inferences as to the present performance of either magnesium-copper sulphide rectifiers or the plate or sprayed-disc type copper oxide rectifier at high currents.

Outside the laboratory and after aging, the efficiency under service conditions approaches 70 to 75 per cent for copper oxide as against 50 to 55 per cent for magnesium-copper sulphide. However, in the type of work discussed by Mr. Kotterman, as well as in numerous other industrial applications, the limited temperature range and inherent fragility of the copper oxide units more than offsets their moderate advantage in efficiency.

In many industrial applications, the selection of a rectifier is based mainly on consideration of space, weight, cost, temperature limitations, ruggedness, and ability to withstand the abuse inherent in unskilled operation or accommodation of temporary overloads. Whenever any or all of these factors are important, magnesium-copper sulphide rectifiers have very definite advantages to offer.

As to probable life, I should like to point out the fact that the plate or sprayed-disc type copper oxide rectifier and heavy-duty magnesium-copper sulphide rectifier are both relatively new and embrace such radical changes in processing and operation current density as to demand reappraisal of their life expectancy on the basis of their respective field performances. The disappointing and unpredictable performance of early plate type copper oxide rectifiers amply demonstrates the error of basing life expectancy on the performance of the more conservatively engineered low-current copper oxide rectifier. Field tests of the later models of both rectifiers are largely limited to two and one-half years or less, over which period each type has given satisfactory service in those applications to which it has been best suited.

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Time-Saving Method for Calculating Induction-Motor Performance

To the Editor:

For studying the theory and calculating the performance of both single and polyphase induction motors, a great many methods have been proposed. These may be grouped as: (*a*) circle diagram, (*b*) analytical, (*c*) equivalent network, (*d*) auxiliary curves.

Of these (*a*) is used at present mainly for purposes of visualization, while (*b*), (*c*), and (*d*) are used for calculation. Most analytical methods are long[6,8] and require considerable time and labor. The equivalent network scheme, using the circuit of Steinmetz, is in process of adoption by the AIEE. Network methods have been used to some extent. They require a minimum of labor, are accurate, and the physical phenomena may be visualized with greater ease. But many engineers are not familiar with their use. Most textbooks indicate but do not give details of procedure. Auxiliary curves for polyphase motors have been described by W. J. Branson,[4] and for single-phase motors by A. F. Puchstein and T. C. Lloyd.[7] Curves are apt to be bulky and not generally available, though they do save labor. The circle diagram has been superseded in practice mainly because it is less convenient and less accurate than its competitors.

It is the purpose of the present effort to give a method based on the classical equations of coupled circuits and to illustrate the results by numerical examples. Practically all textbooks, particularly those which approach the subject from the standpoint of the transformer, show that a polyphase motor behaves as a transformer whose secondary resistance is equal to r_2/s. By similar reasoning, it follows that the single-phase motor behaves as a transformer with two secondaries, each with one-half the reactance in the polyphase motor and with the resistances $\frac{r_2}{2s}$ and $\frac{r_2}{2(2-s)}$, respectively. This approach requires less labor than most methods and ties together the single-phase and polyphase processes.

Polyphase Motor. The solution in this case has the form:
Primary current,

$$I_1 = \frac{V z_2}{z_1 z_2 + x_{12}^2} \qquad (1)$$

in amperes per phase.

Secondary current,

$$I_2 = -\frac{jV x_{12}}{z_1 z_2 + x_{12}^2} \qquad (2)$$

in amperes per phase.
Ratio

$$\frac{I_2}{I_1} = -\frac{jx_{12}}{\frac{r_2}{s} + jx_2} \qquad (3)$$

where

r_1 = resistance of primary in ohms per phase
x_1 = total reactance of primary in ohms per phase
$z_1 = r_1 + jx_1$
r_2 = resistance of secondary reduced to primary in ohms per phase
x_2 = total reactance of secondary reduced to primary in ohms per phase
$z_2 = \frac{r_2}{s} + jx_2$
s = slip as a decimal = 0 to 1 in normal operating range
>1 if machine is driven backward against its torque
<0 if machine is driven above synchronism (generator).
x_{12} = mutual reactance between primary and secondary reduced to primary in ohms per phase. It is equal to the magnetizing reactance for the air gap.

[6] For all numbered references, see list at end of letter.

V = primary terminal electromotive force in volts per phase

Special Cases. For certain purposes, for example to draw the circle diagram, it is convenient to have the following points I_1 and I_2 at zero slip, infinite slip, ideal short circuit, etc.

Useful Relations.

Torque $T = mI_2^2\frac{r_2}{s}$ synchronous watts (4)

= secondary input watts.

m = number of primary phases.

Slip at pull-out,[2]

$$s_{po} = \frac{r_2}{x_2}\sqrt{\frac{1+\left(\frac{r_1}{x_1}\right)^2}{\sigma^2+\left(\frac{r_1}{x_1}\right)^2}} \quad (5)$$

where

$$\sigma = 1-\frac{x_{12}^2}{x_1x_2} = \text{Blondel's leakage factor.} \quad (6)$$

Pull-out torque follows from equations 5, 2, and 4.

Starting torque follows from 2 and 4 with $s = 1$. If desired, convenient curves such as

$$\frac{StT}{POT} = f\left(\frac{r_2}{x_2}\right)$$

may be plotted.

StT = Starting torque

POT = pull-out torque

Reactance for a Given Pull-Out Torque. For any given punchings the ratios $\frac{r_1}{x_1}$, $\frac{r_2}{x_2}$, and $\frac{x_{12}^2}{x_1x_2}$ are nearly constant so long as there is not too much saturation. In any given case, then, these ratios are known or can be found from an exploring calculation. If now the slip at pull-out is found from equation 5, I_2 from 2 substituted in 7, and the result transformed, the following expression for the total reactance and thence the number of turns required to give a prescribed pull-out torque may be obtained:

$$x_1^2 = \frac{mV^2}{T}\cdot\frac{\left(\frac{x_{12}}{x_2}\right)^2\cdot\frac{r_2}{s_{po}}}{\left(\frac{r_1}{x_1}\cdot\frac{r_2}{x_2s_{po}}+\frac{x_{12}^2}{x_1x_2}-1\right)^2+\left(\frac{r_1}{x_1}+\frac{r_2}{x_2s_{po}}\right)^2} \quad (7)$$

Similar expressions have been used in design offices for many years. Their use greatly simplifies and speeds up design procedure, particularly if a list of these ratios has been tabulated. Knowledge of these general facts seems not to have reached design textbooks or electrical-engineering teachers. Similar expressions can be derived also from the equivalent network and in other ways.

If a circle diagram is drawn, I_2 may be measured on the diagram to the same scale as I_1, but the actual value will be (I_2 from circle) $\times\frac{|z_1|}{x_{12}}$. This can be proven by taking the ratio of I_2 from equation 2 to the vector difference between I_1 from equation 1 for slip s and for slip o. This point has puzzled many engineers and few texts explain the reason.

Working Equations and Examples. To illustrate the process, we shall take the main phase of the capacitor motor used by W. J. Morrill[3] and consider it as one phase of a three-phase motor. The constants will be doubled where necessary to give them the values that belong to polyphase operation, thus:

Primary resistance,

$r_1 = 2.02 = R_{1m}$

Primary reactance, total,

$x_1 = 2(33.4+2.79) = 69.59 = 2(X_m+X_{1m})$

Magnetizing reactance for air gap,

$x_{12} = 2\times33.4 = 66.8 = 2X_m$

Secondary resistance,

$r_2 = 4.12 = 2R_2$

Secondary reactance, total,

$x_2 = 2(33.4+1.06) = 68.92 = 2(X_m+X_2)$

Iron loss = 24 watts; friction and windage = 13 watts, 60 cycles, 110 volts, 4 poles. Assuming that slip, $s = 0.05$, the work is set up as follows:

$z_1 = r_1+jx_1 = 2.02+j69.59$

$$\frac{x_{12}^2}{z^2} = \frac{x_{12}^2\left(\frac{r_2}{s}-jx_2\right)}{\left(\frac{r_2}{s}\right)^2+x_2^2}$$

$$= \frac{66.8^2\left(\frac{4.12}{0.05}-j68.92\right)}{\left(\frac{4.12}{0.05}\right)^2+68.92^2} = 31.88-j26.66$$

Machine impedance,

$Z = \text{sum} = 33.90+j42.93$

$= 54.6/51°40'$ ohms

Primary current in amperes per phase,

$$I_1 = \frac{V}{Z} = \frac{110}{54.6/51°40'} = 2.01\sqrt{51°40'}$$

$= 1.25-j1.58$

Adding core loss current,

$$= \frac{Fe}{mV} = \frac{24}{3\times110} = 0.073$$

Total = $1.323-j1.58$

Supply current,

$I = \text{sum} = 1.323-j1.58 = 2.06\sqrt{50°0'}$

The core loss can also be included by writing for each, x_1, x_2, and x_{12}, an expression of the form $x(\sin\alpha+j\cos\alpha)$ in equations 1 and 2, etc., where α is the angle of advance due to core loss. Another way is to add the core loss to friction and windage.

Input,

$P = 3\times110\times1.323 = 437$ watts

Secondary current,

$$I_2 = \frac{x_{12}}{|z_2|}I_1 = \frac{66.8\times2.01}{\sqrt{\left(\frac{4.12}{0.05}\right)^2+68.92^2}} = 1.25$$

Torque,

$$T = 3\times1.25^2\times\frac{4.12}{0.05} = 387 \text{ synchronous watts}$$

$$= \frac{7.04\times387}{1{,}800} = 1.51 \text{ pound-feet}$$

Power converted,

$W_c = (1-s)T = 0.95\times387 = 368$ watts

Friction and windage loss = 13 watts

Output,

$W_0 = 355$ watts

Losses,

$437-355 = 82$ watts

Also for check,

Primary copper loss,

$3I_1^2r_1 = 3\times2.01^2\times2.02 = 24.6$ watts

Secondary copper loss,

$3I_2^2r_2 = 3\times1.25^2\times4.12 = 19.4$ watts

Iron loss = 24.0 watts

Friction and windage loss = 13.0 watts

Total loss = 81.0 watts

These results agree closely with those obtained from the equivalent network of Steinmetz. Other networks are suggested in Behrend's "Induction Motor."[3]

Single-Phase Motor. For single-phase operation, as already indicated, the three circuit equations are set up with one-half the values for certain quantities that are used for polyphase motors, thus

$$x_{12}' = \frac{x_{12}}{2},\ r_2' = \frac{r_2}{2},\ x_2' = \frac{x_2}{2}$$

If

f = frequency of supply in cycles per second

I_f = forward rotor current of frequency sf

I_b = backward rotor current of frequency $(2-s)f$

$z_f = \frac{r_2'}{s}+jx_2'$ = rotor impedance to forward current

$z_b = \frac{r_2'}{2-s}+jx_2'$ = rotor impedance to backward current

both reduced to primary in ohms per phase. The solutions are

$$I_1 = \frac{Vz_fz_b}{z_1z_bz_f+x_{12}'^2(z_b+z_f)} \quad (1')$$

$$I_f = \frac{-jVx_{12}'z_b}{z_1z_bz_f+x_{12}'^2(z_b+z_f)} \quad (2')$$

$$I_b = \frac{-jVx_{12}'z_f}{z_1z_bz_f+x_{12}'^2(z_b+z_f)} \quad (3')$$

Special Cases. As before, when it is desirable to have I_1, I_f, and I_b at zero slip, infinite slip, etc., these may be obtained from equations 1' to 3'.

Working Equations. For this purpose we choose,

$$I_1 = \frac{V}{z_1+\frac{x_{12}'^2}{z_f}+\frac{x_{12}'^2}{z_b}} \quad (4')$$

$$I_f = \frac{x_{12}'}{|z_f|} I_1 \qquad (5')$$

$$I_b = \frac{x_{12}'}{|z_b|} I_1 \qquad (6')$$

If skin effect is marked as in deep-slot rotors, r_2' and x_2' may be given different values in the forward and backward terms.

Examples and Further Formulas. For this purpose, Morrill's motor with the starting phase open will again be used. The procedure then is at slip

$s = 0.05$:

Primary impedance,

$$z_1 = 2.02 + j69.59$$

Rotor forward impedance,

$$\frac{x_{12}'^2}{z_f} = \frac{33.4^2\left(\frac{2.06}{0.05} - j34.46\right)}{\left(\frac{2.06}{0.05}\right)^2 + 34.46^2} = 15.91 - j13.31$$

Rotor backward impedance,

$$\frac{x_{12}'^2}{z_b} = \frac{33.4\left(\frac{2.06}{1.95} - j34.46\right)}{\left(\frac{2.06}{1.95}\right)^2 + 34.46^2} = 0.99 - j32.40$$

Machine impedance,

$$\text{sum} = Z = 18.92 + j23.88$$
$$= 30.5\ \underline{/51°40'}\ \text{ohms}$$

Primary current,

$$\frac{V}{Z} = \frac{110}{30.5\underline{/51°40'}} = 3.61\sqrt{51°40'} = 2.24 - j2.83$$

Core loss current, primary,

$$\frac{F_e}{2V} = \frac{24}{2\times 110} = 0.11 + j0$$

Supply current,

$$I = \text{sum} = 2.35 - j2.83$$
$$= 3.68\sqrt{50°20'}\ \text{amperes}$$

It was assumed that the line supplies one-half the polyphase core loss directly and the rotor the other half $\times(1-s)^2$. If it is assumed that the line supplies all the core loss directly, the results will not differ greatly from those of the equivalent-network solution. The method of writing x_1, x_2', and x_{12}' in the form $x(\sin\alpha + j\cos\alpha)$ can also be used.

Secondary forward current,

$$I_f = \frac{33.4\times 3.61}{\sqrt{\left(\frac{2.06}{0.05}\right)^2 + 34.46^2}} = 2.24\ \text{amperes}$$

Secondary backward current,

$$I_b = \frac{33.4\times 3.61}{\sqrt{\left(\frac{2.06}{1.95}\right)^2 + 34.46^2}} = 3.49\ \text{amperes}$$

Forward torque,

$$T_f = I_f^2 \cdot \frac{r_2'}{s} = 2.24^2 \times \frac{2.06}{0.05} = 207\ \text{synchronous watts}$$

Backward torque,

$$T_b = I_b \cdot \frac{r_2'}{2-s} = 3.49^2 \times \frac{2.06}{1.95} = 13\ \text{synchronous watts}$$

Resultant torque,

$$T = T_f - T_b = 207 - 13 = 194\ \text{synchronous watts}$$

Power converted,

$$W_c' = (1-s)T = 0.95\times 194 = 184\ \text{watts}$$

Iron loss carried by rotor,

$$(1-s)^2\frac{F_e}{2} = 0.95^2\times 12 = 11\ \text{watts}$$

Power converted,

$$W_c = 184 - 11 = 173\ \text{watts}$$

Friction and windage = 13 watts
Output = 160 watts

Shaft torque,

$$\frac{160}{1-.05} = 168\ \text{synchronous watts, or}$$

$$\frac{112.5\times\text{synchronous watts}}{\text{syn.}} = 10.5\ \text{ounce-feet,}$$

where "syn" is the synchronous speed in revolutions per minute.

Input,

$$W_i = 110\times 2.35 = 258\ \text{watts}$$

Losses,

$$258 - 160 = 98\ \text{watts}$$

Also for check,
Iron loss,

$$12 + 11 = 23\ \text{watts}$$

Friction and windage = 13 watts

Primary copper loss,

$$I_1^2 r_1 = 2.61^2\times 2.02 = 26.4\ \text{watts}$$

Secondary copper loss, forward,

$$I_f^2 r_2' = 2.24^2\times 2.06 = 10.7\ \text{watts}$$

Secondary copper loss, backward,

$$I_b^2 r_2' = 3.69^2\times 2.06 = 25.1\ \text{watts}$$

Total loss = 98.2 watts

Slip at Pull-Out. An expression for this can be derived in a manner similar to that outlined for the polyphase motor. This leads to a sixth degree equation which is not suitable for practice. In its stead, a process outlined by C. G. Veinott[1,6] may be used. Let

$$\alpha = \frac{1}{2}\,\text{ctn}^{-1}\frac{r_2}{X} \cong \frac{1}{2}\,\text{ctn}^{-1}\frac{4.12}{4.91} = 25°0'$$

$$X \cong x_1 + x_2 = 2.79 + 2.12 = 4.91$$

$$\tan\alpha = 0.466,$$

then speed at pull-out,

$$S_{po} \cong \sqrt{1 - 1.05\tan\alpha\cdot\frac{r_2}{X}} =$$

$$\sqrt{1 - 1.05\times 0.466\times\frac{4.12}{4.91}} = 0.768 \qquad (7')$$

and slip at pull out = $s_{po} \cong 1 - 0.768 = 0.232$.

Reactance to Give a Prescribed Pull-Out Torque. When the ratios $\frac{r_1}{x_1}$, $\frac{r_2'}{x_2'}$, and $\frac{x_{12}'^2}{x_1x_2'}$ for a set of punchings to be used are known, let

$$r_f = \frac{r_2'}{s}, \quad r_b = \frac{r_2'}{2-s}$$

$$a = r_f\left[1 + \left(\frac{r_f}{x_2'}\right)^2\right]$$

$$b = r_b\left[1 + \left(\frac{r_b}{x_2'}\right)^2\right]$$

$$A = \frac{r_1}{x_1}\cdot\frac{r_b}{x_2'}\cdot\frac{r_f}{x_2'} + \frac{x_{12}'^2}{x_1x_2}\cdot\left(\frac{r_b}{x_2'} + \frac{r_f}{x_2'}\right) - \left(\frac{r_1}{x_1} + \frac{r_b}{x_2'} + \frac{r_f}{x_2'}\right)^2$$

$$B = \left[\frac{r_1}{x_1}\cdot\frac{r_b}{x_2'} + \frac{r_b}{x_2'}\cdot\frac{r_f}{x_2'} + \frac{r_1}{x_1}\cdot\frac{r_f}{x_2'} + \frac{2x_{12}'^2}{x_1x_2'} - 1\right]^2$$

then

$$x_1^2 = \frac{V^2}{T}\cdot\left(\frac{x_{12}'}{x_2'}\right)^2\cdot\frac{a-b}{A+B}\ \text{ohms}^2 \qquad (8')$$

These relations can be further simplified for practice and have been so used for many years. When x_1 is known, the number of stator turns required to give a specified pull-out torque follow at once.

Ideal No-Load Speed. When there is no iron loss and no friction, the torque is zero when

$$T_f = T_b$$

Making the appropriate substitutions,[2] this gives for the corresponding slip

$$s_0 = \sqrt{1 - \left(\frac{r_2'}{x_2'}\right)^2} \qquad (9')$$

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7. Single-Phase Induction Motor Performance, A. F. Puchstein and T. C. Lloyd. Electrical Engineering, October 1937, pages 1277–84.

8. Revolving Field Theory of the Capacitor Motor, W. J. Morrill. AIEE Transactions, volume 48, 1929, pages 614–29.

9. The Induction Motor (a book), B. A. Behrend. McGraw-Hill Book Company, New York, 1921, pages 44, 208–09, 226.

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Books Received

The following new books are among those recently received at the Engineering Societies Library. Unless otherwise specified, books listed have been presented by the publishers. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the prefaces of the books in question.

THE THEORY AND USE OF THE COMPLEX VARIABLE. By S. L. Green. New York and Chicago, Pitman Publishing Corporation, 1939. 136 pages, diagrams, 9 by 6 inches, cloth, $3.00. An introductory account of the subject of the complex variable and conformal transformation, with some indication of applications to problems of mathematical physics, aeronautics, and electrical engineering. The mathematical requirements comprise some knowledge of calculus and analytical plane geometry. Exercises are included.

LUBRICANTS AND LUBRICATION. By J. I. Clower. New York and London, McGraw-Hill Book Company, 1939. 464 pages, illustrated, 9 by 6 inches, cloth, $5.00. The first ten chapters present the fundamentals of lubricants and lubrication in such a way as to enable the student to analyze the requirements of most equipment. The following six chapters apply the basic principles to various machines and make specific recommendations for the analysis of equipment.

SCIENCE TODAY AND TOMORROW. By W. Kaempffert. New York, The Viking Press, 1939. 275 pages, tables, 8½ by 5 inches, cloth, $2.50. The great events on the horizon in astronomy, physics, chemistry, biology, electricity, and other sciences are presented in non-technical language. The author also predicts some probable or possible future extensions and their influence on the social organization.

SPARKS, LIGHTNING, COSMIC RAYS. An Anecdotal History of Electricity. By D. C. Miller. New York, Macmillan Company, 1939. 192 pages, illustrated, 9 by 6 inches, cloth, $2.50. Embodies the Christmas lectures for young people at the Franklin Institute in 1937. The nature of electricity, from the experiments with amber by the Greek philosophers to the latest phenomena of cosmic rays, is presented by anecdotal reference to the many significant experiments and discoveries made by the inspired investigators in that field. The second section of the three comprising the book is devoted to Benjamin Franklin.

SUPERCONDUCTIVITY. By D. Shoenberg. Cambridge, England, University Press; New York, Macmillan Company, 1938. 111 pages, diagrams, charts, 8½ by 5½ inches, paper, $1.75. The phenomenon of superconductivity as exhibited by certain metals, metallic compounds, and alloys is discussed, mainly from the point of view of recent developments. The experimental results cited are for the purpose of making clear the essential principles involved. Bibliography at the end of each chapter and with the appendix of numerical data.

STRATEGIC MINERAL SUPPLIES. By G. A. Roush. New York and London, McGraw-Hill Book Company, 1939, 485 pages, diagrams, etc., 9½ by 6 inches, cloth, $5.00. Presents a concise picture, from both a military and general industrial viewpoint, of the status of the United States with respect to supplies of those materials of mineral origin of which the domestic supply is inadequate. Twelve minerals, mostly metals, are discussed in detail as to uses, substitutes, ore reserves, sources of supply, imports, exports, stocks, tariff, and political and commercial control, as they affect the domestic situation.

AMERICAN DIESEL ENGINES. By L. H. Morrison. Second Edition. New York and London, McGraw-Hill Book Company, 1939. 489 pages, illustrated, 9½ by 6 inches, cloth, $5.00. Planned to give factory executives and operating engineers information that will enable them to select the best engine for their purposes, and operate and maintain it efficiently. It includes detailed descriptions of all American-made engines. The new edition has been revised extensively.

INTERNAL COMBUSTION ENGINES. By L. C. Lichty. Fifth edition. New York and London, McGraw-Hill Book Company, 1939, 603 pages, illustrated, 9 by 6 inches, cloth, $4.50. This textbook first develops the theoretical principles and then illustrates their application to the analysis, design, and operation of the internal-combustion engine and its parts. Changes include a simplification of the method of analyzing thermodynamic processes, a chapter on air-standard cycle analysis, revision of the chapters on fuels, detonation and fuel injection, more material on combustion-chamber design and air cooling, and thorough revision throughout. Previous editions were under joint authorship of Robert L. Streeter.

THE RECTIFICATION OF ALTERNATING CURRENT. By H. Rissik. London, English Universities Press; Hodder and Stoughton, 1938. 219 pages, illustrated, 9 by 6 inches, cloth, 21s. Fundamental circuit relations and the general characteristics of rectifier circuits are discussed in Part I. Part II covers the physical principles underlying rectification phenomena, electric discharges, boundary layers, etc. In Part III four methods of a-c rectification are described: mechanical, electron discharge, arc discharge, and by unipolarity of boundary layers. The book is intended for both students and practicing engineers and has a large bibliography.

ABSORPTION SPECTROPHOTOMETRY AND ITS APPLICATIONS; Bibliography and Abstracts 1932 to 1938. By O. J. Walker. London, Engineering and Allied Sciences, Ltd., 1939. 68 pages, 10 by 6 inches, linen, apply. A comprehensive list of references covering the developments and applications of absorption spectrophotometry for the period 1932 to 1938. In order to facilitate the task of obtaining quantitative absorption data concerning any particular problem, the references have been classified under various general headings and are numbered serially. There is an author index.

ATM (Archiv für technisches Messen) Lfg. 97 and 98, July and August, 1939. Munich and Berlin, Oldenbourg. Pages T85-112, illustrated, 12 by 8 inches, paper, 1.50 rm. each. Two numbers of a monthly publication containing classified articles upon various types of apparatus and methods for technical measurements. Certain numbers also contain descriptions of specific instruments manufactured by German companies.

AUDEL'S NEW RADIOMAN'S GUIDE. By E. P. Anderson. New York, Theo. Audel and Company, 1939, 756 pages, illustrated, 7 by 5 inches, cloth, $4.00. Covers the fundamentals of sound, electricity, and radio principles; describes broadcasting and receiving equipment, including design, operation, and maintenance details; and discusses allied apparatus, such as marine and aircraft communication, public address systems, the radio compass and beacons, automatic alarms, and electronic devices. Underwriters' rules, standards, symbols, abbreviations, and units are given, and questions or problems with answers are included in various chapters.

Deutsches Museum, Abhandlungen und Berichte, Jg. 11, Heft 2. GEORG SIMON OHM, by J. Zenneck. Berlin, VDI-Verlag, 1939, 57 pages, illustrated, 8 by 6 inches, paper, 0.90 rm. The life and work of Ohm are briefly related, with a further section discussing Ohm as a teacher, the recognition he received, and his personal appearance. Short bibliography.

DIESEL ENGINEERING HANDBOOK 1939-1940. De luxe edition. Edited by L. H. Morrison. New York, Diesel Publications, 1939, 940 pages, illustrated, 9 by 6 inches, cloth, $6.00. This handbook, revised and enlarged, provides practical up-to-date information upon the operation and maintenance of Diesel engines, valuable both to the owner and operator. The treatment is exhaustive and profusely illustrated from actual practice. Two chapters of engineering fundamentals are devoted to brief description of useful general engineering terms and equipment.

FAULTS AND FAILURES IN ELECTRICAL PLANT. By R. Spieser and others; translated by E. Hunking. London, Sir Isaac Pitman and Sons; New York, Pitman Publishing Corporation, 1939, 408 pages, illustrated, 8 by 6 inches, cloth, $10.00. The paucity of collected information on electrical plant troubles has inspired the translation from the German of this book on the causes, results, cure, and prevention of faults and failures in heavy current machinery, apparatus, and plant. The first three parts cover installation and operational faults of electrical machines, transformers, and auxiliary apparatus. Part IV considers the materials employed and the troubles directly resulting from them.

HUMAN-RELATIONS MANUAL FOR EXECUTIVES. By J. Heyel. New York and London, McGraw-Hill Book Company, 1939. 253 pages, diagrams, etc., 8 by 5 inches, cloth, $2.00. Ideas for selecting, developing, stimulating, safeguarding, and guiding the working force are presented in the form of case examples of what actual companies are doing successfully to solve their personnel problems. Application check points, consisting of pertinent questions on the preceding material, accompany each chapter.

INTRODUCTION TO CHEMICAL PHYSICS. By J. C. Slater. New York and London, McGraw-Hill Book Company, 1939. 552 pages, diagrams, etc., 9 by 6 inches, cloth, $5.00. The purpose of this book is to provide a unified presentation of the subjects common to both physics and chemistry, especially for those who wish to obtain the maximum knowledge of chemical physics with the minimum of theory.

MARINE DIESEL MANUAL. Edited by L. R. Ford. Diesel Publications, New York, 1939, 207 pages, illustrated, 6 by 5 inches, paper, $0.50. Covers the principles, types, and details of marine Diesel engines, including fuel systems, lubrication, operation and maintenance instructions, auxiliary equipment, and electric and gear drives.

MATTER AND LIGHT, THE NEW PHYSICS. By L. de Broglie; translated by W. H. Johnston. New York, W. W. Norton and Company, 1939, 300 pages, diagrams, etc., 9 by 5 inches, cloth, $3.50. A collection of studies on contemporary physics, some written from the general and others from a more metaphysical point of view. The subjects include a general survey of contemporary physics, matter and electricity, light and radiation, wave mechanics, philosophical studies on quantum physics, and other philosophical studies.

ASTM STANDARDS ON ELECTRICAL INSULATING MATERIALS. Specifications, Methods of Testing. Prepared by Committee D-9. October 1939. Philadelphia, American Society for Testing Materials. 306 pages, illustrated, 9 by 6 inches, paper, $2.00 (ASTM members, $1.50). In addition to the current report of the responsible committee, this pamphlet contains 11 standard and 18 tentative methods of testing for electrical insulating materials, and also 3 specifications. In addition, there are 10 specifications covering certain rubber and textile products and methods of testing shellac.

ELECTRICAL COMMUNICATION. By A. L. Albert. Second edition. John Wiley and Sons, New York, 1940. 534 pages, illustrated, 9½ by 6 inches, cloth, $5.00. This textbook covers the whole field of electrical communication by wire and wireless transmission of code and speech. Telegraphy, telephony, and radio are treated not as isolated subjects, but to show their interrelations in providing an adequate, economical communication service. This edition has been revised and enlarged, and bibliographies brought up to date.

ELECTRICAL TIMEKEEPING. By F. Hope-Jones, with a foreword by H. S. Jones. N.A.G. Press, Ltd., London, 1940. 275 pages, illustrated, 9 by 5½ inches, cloth, 10s. An horologist gives an account of the efforts, extending over 100 years, to obtain accurate timekeeping by the application of electricity. Includes a digest of the historical chapter of "Electric Clocks", by the same author. It also sets forth the principles essential to accurate timekeeping, describes the theory of the free pendulum and its application, and considers synchronous-motor clock, telescope drives, and other horological matters.

ENGINEERING DRAWING, PRACTICE AND THEORY. By I. N. Carter. Scranton, Pa., International Textbook Company, 1939. 264 pages, illustrated, 11½ by 8½ inches, cloth, $2.50. Combines descriptive geometry and engineering drawing in a single course of study covering both theory and practice. Considerable saving of time by elimination of duplication of classroom work is claimed. The book covers the fundamental principles of machine, structural, and topographic drafting, according to accepted drafting-room methods.

FUNDAMENTAL PROCESSES OF ELECTRICAL DISCHARGE IN GASES. By L. B. Loeb. New York, John Wiley and Sons, 1939. 717 pages, illustrated, 9 by 6 inches, cloth, $7.00. The topics discussed comprise ionic mobilities, ionic and electronic recombination processes, diffusion of ions and electrons, electron mobilities, energy distribution functions of electrons in gases, electron-attachment and negative-ion formation, conduction currents, and the Townsend coefficients. Each is introduced from the classical point of view and carried through the subsequent experimentation and theory to the present-day interpretation. The final chapters present the application to the problems of spark discharge, the glow, and the arc. References.

Great Britain, Mines Department. REPORT OF H.M. ELECTRICAL INSPECTOR OF MINES FOR THE YEAR 1938. London, His Majesty's Stationery Office, 1939. 45 pages, tables, 10 by 6 inches, paper, 9d. (Obtainable from British Library of Information, 50 Rockefeller Plaza, New York, 25c.) In addition to statistics on the electrical equipment used in the mines, the report contains statistics and analyses of accidents attributed to the use of electricity.

HANDBOOK OF PHOTOGRAPHY. Edited by K. Henney and B. Dudley. McGraw-Hill Book Company, Whittlesey House, New York, 1939. 871 pages, illustrated, 9 by 6 inches, leather, $7.50. A one-volume encyclopedia of photography, the work of 23 specialists, presents the view and technique of the photographic process and the scientific basis underlying photography and its applications. Photomicrography, motion pictures, color, speed, and infrared photography, and other specialized adaptations are covered. Bibliographies and reference tables.

PRINCIPLES OF TELEVISION ENGINEERING. By D. G. Fink. McGraw-Hill Book Company, New York and London, 1940. 541 pages, illustrated, 9½ by 6 inches, cloth, $5.00. Gives information on the fundamental processes of television reception and transmission, and also on design and modern equipment. The presentation is arranged in the logical sequence of events in television transmission, beginning with the camera, through the subsidiary amplifying and transmitting equipment, radiation through space, reception and amplification, detection and image reproduction. Standards, recommended practices, definitions, and names of controls are appended.

Institute Activities

Preliminary Program Arranged for 1940 Summer Convention at Swampscott

The 1940 AIEE summer convention, which will be held in Swampscott, Mass., June 24–28, will provide a business and technical program of broad interest, with opportunity for sports, trips, and social recreation. Swampscott, on Boston's north shore, affords unlimited opportunity for healthful outdoor enjoyment, and the committee expects to make this convention a gathering place for many family groups. The technical program has been so arranged that the sessions on communication and electronics, as well as the frequency-modulation demonstration, occur during the early part of the convention to permit members interested in these subjects to attend the 15th annual convention of the Institute of Radio Engineers, at Hotel Statler, Boston, Mass., June 27–29. Members also are reminded that as the semiannual meeting of The American Society of Mechanical Engineers is being held in Milwaukee, Wis., June 17–20, those traveling from the west may conveniently attend both meetings.

FREQUENCY-MODULATION DEMONSTRATION

Wednesday evening, June 26, a talk on frequency modulation, with demonstrations, will be given by W. L. Everitt, Ohio State University. The talk will cover the history of frequency modulation, its fundamental principles of operation, what it aims to accomplish, and a comparison of its results with those which can be obtained by amplitude modulation at both broadcast and ultrahigh frequencies.

One of the most dramatic effects of frequency modulation will be shown, that is, that when two stations are operating on the same frequency, if one signal exceeds the other by a ratio of two to one or more, only the louder signal is heard. To demonstrate this two small frequency-modulated transmitters which operate on the same frequency and whose output can be controlled by Variacs in the plate supply of the final amplifiers are used. By controlling the output of either or both of these transmitters one or the other signal can be made to dominate. The transmitters will be amplitude-modulated as well, to show the difference between the two types of modulation. Speech is used to modulate one transmitter and music on the other.

Arrangements have been made through the Yankee Network to make a special broadcast from Paxton to show the high quality that can be obtained from a station some 50 miles away.

TECHNICAL CONFERENCES

Seven technical conferences have been tentatively scheduled on the following subjects: communication networks, standards, load swings, test codes, nonlinear analysis, introducing modern statistical technique to electrical engineers, and dielectric measurements in the field. The scope and objectives in so far as known are given. Although some of the material in the conferences is the basis of committee work the general membership is invited to attend and participate freely in the general discussion.

Standards (Tuesday, June 25, 2:00 p.m.). Subjects to be discussed are: first, the work for the proposed co-ordinating committee 7 on conduction; second, the scope of co-ordinating committee 5 on basic theories and units; and, third, a discussion of short-time ratings of apparatus continuing the work of co-ordinating committee 4, which has been revising Standard No. 1.

As work for the proposed co-ordinating committee 7 on conduction, the co-ordination of ratings of wire and conductors with

Annual Meeting

The annual meeting of the American Institute of Electrical Engineers will be held at the New Ocean House, Swampscott, Mass., at 10 a.m. on Monday, June 24, 1940. This will constitute one session of the summer convention.

At this meeting, the annual report of the board of directors and the report of the committee of tellers on the ballots cast for the election of officers will be presented.

Such other business, if any, as properly may come before the annual meeting may be considered.

(*Signed*) H. H. HENLINE
National Secretary

Tentative Schedule of Events

All Sessions and Conferences Will Be Held at the New Ocean House

Monday, June 24

Morning	Registration
10:00 a.m.	Annual Meeting Reports, presentation of prizes for papers, presentation of Lamme Medal, and president's address
2:00 p.m.	Conference of officers, delegates, and members
4:00 p.m.	Women's tea and musicale
Evening	Dance and reception

Tuesday, June 25

Morning	Opening of women's golf tournament
9:00 a.m.	Electronics
9:00 a.m.	Power transmission
9:00 a.m.	Standards
9:00 a.m.	Automatic stations and basic sciences
Noon	Luncheon for women golfers at Tedesco Country Club
Afternoon	Putting contest with prizes for women not in tournament
2:00 p.m.	Conference of Student Branch counselors
2:00 p.m.	Conference on communication networks
2:00 p.m.	Conference on standards
2:00 p.m.	Conference on load swings
Afternoon	Deep-water cruise on fishing schooner "Gertrude L. Thebaud"—tickets $2.50
Evening	Searchlight drill by naval vessels off Swampscott shore Special motion pictures in ballroom

Wednesday, June 26

9:00 a.m.	Communication
9:00 a.m.	Transportation
9:00 a.m.	Testing of insulation
2:00 p.m.	Conference of officers, delegates, and members, continued
Afternoon	Bridge party for women
Evening	Shore dinner on the rocks and beach adjoining New Ocean House Frequency-modulation demonstration Dancing

Thursday, June 27

10:00 a.m.	Joint general session with the American Engineering Council
Noon	Board of directors luncheon meeting
2:00 p.m.	Conference on test codes
2:00 p.m.	Conference on nonlinear analysis
2:00 p.m.	Conference on introducing modern statistical technique to electrical engineers
2:00 p.m.	Conference on dielectric measurements in the field
Evening	Formal banquet and dance—special decorations, award of women's sport prizes, and orchestral music

Friday, June 28

9:00 a.m.	Protective devices
9:00 a.m.	Instruments and measurements
9:00 a.m.	Electrical machinery

ratings of the apparatus they serve, has been suggested. This would probably involve such questions as the rating of fuses, circuit breakers, starting currents, short and overtime ratings, flicker, etc.

As scope for the work of co-ordinating committee 5 discussion will evolve about the use of the rationalized system for deriving the basic units.

Load Swings (Tuesday, June 25, 2:00 p.m.). This conference sponsored by the committee on power generation will be devoted to the subject of load swings as related to turbine-generator governing and stability. A subcommittee is preparing a program which it is hoped will be augmented by voluntary contributions from those in attendance. From the discussion evolved specific topics will be selected and authors invited to prepare formal papers for the winter convention.

Introducing Modern Statistical Technique to Electrical Engineers (Thursday, June 27, 2:00 p.m.). This conference is intended to show to those unacquainted with statistical methods what information and economy may be secured by this technique and how statistics will add to the effectiveness of engineering effort. Informal talks will be given on statistical control in manufacturing, statistics applied to research, the building up of engineering tolerances, and statistical quality control. Following these talks a general discussion will be lead by Doctor W. S. Shewhart, Bell Telephone Laboratories, Inc.; Doctor R. Rudenberg, Harvard University; and A. J. Lacock, General Electric Company. In this conference attempts will be made to discuss the use of the statistical method by means of concrete cases rather than theory, but for those interested in the subject a book by Doctor Shewhart entitled "Statistical Method From the Viewpoint of Quality Control," is recommended to render the discussion more interesting.

INSPECTION TRIPS

On Tuesday, June 25 and Wednesday, June 26, trips are being arranged to interesting industrial plants, such as Champion Lamp Works, Christian Science Publishing Society, General Electric Company, Hygrade-Sylvania Corporation, Lynn Gas and Electric Company, North Eastern Telephone and Telegraph Company—Lynn Exchange, Naumkeag Steam Cotton Company, and United Shoe Machinery Company. On Wednesday, plans have been made for an industrial trip to L Street Station, Boston Edison Company, Boston Fish Pier, and Sumner Tunnel, and a scenic and historical trip to Lexington, Concord, and Bunker Hill, and on Thursday, for visits to Harvard University and Massachusetts Institute of Technology (atom-smashing, wind-tunnel, etc.), and for a trip around historic Boston, including the glass flowers at Harvard.

SPORTS

Throughout the convention facilities will be available for golf, tennis, sailing, soft ball, horse shoes, fish, and chips. As usual, there will be the annual tournaments for the Mershon golf and tennis trophies and the medal play for the Lee trophy.

National • • • •

First Fortescue Fellowship Awarded

Norman Z. Alcock, Kingston, Ontario, Canada, has been chosen to receive the Charles LeGeyt Fortescue Fellowship for 1940–41, the first to be awarded. Terms and provisions of the fellowship, which is administered by a special committee of the AIEE, were described in the January 1940 issue, page 42. Mr. Alcock, who graduates this year from Queens University, Kingston, will use the award for graduate study in electrical engineering at California Institute of Technology, specializing in

Tentative Technical Program (in Part)

Photo-offset copies of authors' manuscripts, except addresses, may be obtained in advance of the convention by writing to the AIEE Order Department, 33 West 39th Street, New York, N. Y. Only numbered papers will be available in advance-copy form. If ordered by mail, price 10 cents per copy; if purchased at Institute headquarters or at the convention, 5 cents per copy. Mail orders (particularly from out-of-town members) are advisable, inasmuch as an adequate supply of each paper at the meeting cannot be assured. Coupon books in $1.00 and $5.00 denominations are available for those who wish to avoid remittance by check or otherwise. Most of the papers ultimately will be published in ELECTRICAL ENGINEERING or the TRANSACTIONS.

Tuesday, June 25

9:00 a.m. Standards

40-92. REFERENCE VALUES FOR TEMPERATURE, PRESSURE, AND HUMIDITY. **P. L. Bellaschi** and **P. H. McAuley**, Westinghouse Electric and Manufacturing Company

40-93. RATIONALIZATION OF SHORT-TIME AND INTERMITTENT RATINGS OF ELECTRICAL APPARATUS AND WIRING. **R. E. Hellmund** and **P. H. McAuley**, Westinghouse Electric and Manufacturing Company

40-94. RATING OF POTENTIAL DEVICES. **P. O. Langguth**, Westinghouse Electric and Manufacturing Company, and **J. E. Clem**, General Electric Company

40-95. STANDARDIZATION PROBLEMS ON FRACTIONAL-HORSEPOWER MOTORS. **C. G. Veinott**, Westinghouse Electric and Manufacturing Company

40-96. EFFECT OF LOAD FACTOR ON OPERATION OF POWER TRANSFORMERS BY TEMPERATURE. **V. M. Montsinger**, General Electric Company

Wednesday, June 26

9:00 a.m. Testing of Insulation

40-81. LOW-VOLTAGE D-C MEASUREMENTS ON ELECTRICAL INSULATING OILS. **J. L. Onclay** and **W. C. Hollibaugh**, Massachusetts Institute of Technology

40-82. RAPID RECORDING ALTERNATING-CURRENT BRIDGE. **W. Mikelson** and **H. W. Bousman**, General Electric Company

40-84. A METHOD FOR DETECTING THE IONIZATION POINT OF ELECTRICAL APPARATUS. **G. E. Quinn**, Consolidated Edison Company of New York, Inc.

Friday, June 28

9:00 a.m. Protective Devices

40-85. A HIGH POWER OIL-LESS CIRCUIT INTERRUPTER USING WATER. **W. M. Leeds**, Westinghouse Electric and Manufacturing Company

40-103. A HIGH-SPEED DIFFERENTIAL RELAY FOR GENERATOR PROTECTION. **W. K. Sonneman**, Westinghouse Electric and Manufacturing Comany.

9:00 a.m. Instruments and Measurements

40-88. AN IMPROVED TYPE OF DIRECT-CURRENT WATTMETER OF THE SHUNTED TYPE. **Paul MacGahan**, Westinghouse Electric and Manufacturing Company

40-89. COMPUTATION OF ACCURACY OF CURRENT TRANSFORMERS. **A. T. Sinks**, General Electric Company

40-90. NEW INSTRUMENTS FOR RECORDING LIGHTNING CURRENTS. **C. F. Wagner** and **G. D. McCann**, Westinghouse Electric and Manufacturing Company

40-91. THE OUTPUT AND OPTIMUM DESIGN OF PERMANENT MAGNETS SUBJECTED TO DEMAGNETIZING FORCES. **A. J. Hornfeck**, Bailey Meter Company, and **R. F. Edgar**, General Electric Company

40-97. A NEW HIGH-SPEED THERMAL WATTMETER. **John H. Miller**, Weston Electrical Instrument Corporation

9:00 a.m. Electrical Machinery

40-98. AN EXTENSION OF THE METHOD OF SYMMETRICAL COMPONENTS USING LADDER NETWORKS. **Waldo V. Lyon**, Massachusetts Institute of Technology

40-99. EFFECTIVE RESISTANCE TO ALTERNATING CURRENTS OF MULTI-LAYERED WINDINGS. **Edward Bennett**, University of Wisconsin, and **Sidney C. Larson**, General Electric X-Ray Corporation

40-100. TRANSIENT STARTING TORQUES IN INDUCTION MOTORS. **A. M. Wahl** and **L. A. Kilgore**, Westinghouse Electric and Manufacturing Company

40-101. DEAD POINTS IN SQUIRREL-CAGE MOTORS. **Quentin Graham**, Westinghouse Electric and Manufacturing Company

40-102. PERFORMANCE OF TRAVELING WAVES IN COILS AND WINDINGS. **R. Rudenberg**, Harvard University

NOTE Papers tentatively scheduled for the technical sessions in so far as known at the time of going to press are announced. Papers to be scheduled in the remaining sessions will be announced in the June issue of ELECTRICAL ENGINEERING.

Future AIEE Meetings

Summer Convention
Swampscott, Mass., June 24–28, 1940

Pacific Coast Convention
Los Angeles, Calif., August 26–30, 1940

Middle Eastern District Meeting
Cincinnati, Ohio, October 9–11, 1940

Winter Convention
Philadelphia, Pa., January 27–31, 1941

communications under Professor R. W. Sorensen. He has won six scholarships and prizes during his course at Queens, which he entered on the Sir Sandford Fleming matriculation scholarship in 1936.

1940 Year Book Available

The 1940 edition of the AIEE Year Book has been issued, in accordance with 1939–40 budget provisions. Addresses are corrected as of February 29, 1940. Copies already have been distributed to all national, District, and Section officers, Student Branch counselors, and all members of national committees. Other members desiring copies may secure them by writing to the AIEE order department, 33 West 39th Street, New York, N. Y. The Year Book is not available to nonmembers of the Institute, nor its use permitted for commercial, promotional, or other circularization purposes.

Section • • • •

Programs Contribute to Community Life

In Pittsfield, Mass., the AIEE Section has fostered a program of activities from which the citizens of the town benefit greatly. For a small charge, they may attend educational lectures on astronomy, exploration, zoology, aviation, photography, medicine, and similar subjects.

The Section's activities consist of a series of popular lectures, a series of technical lectures, not necessarily concerned with members' own work, and a series of colloquia, highly technical discussions of specific interest to the members and their jobs.

To attend the five popular lectures each year nonmembers of the Institute must become local members of the Section, at a charge of $1.50, with no guest privilege. To attend the technical-lecture series local members must buy another ticket for $1.00.

Formerly, the Section sold for $2.00 tickets which entitled the holder and a woman guest to attend all popular and technical lectures. The price was increased partly to maintain a high standard and partly because speakers were costing more, but mainly because the number of people who wanted tickets became overwhelming. Even with the higher charge the Section had to limit the number of tickets sold.

For several years, the local membership has averaged between 1,100 and 1,400. About 400 tickets are given to Institute members and their wives. The maximum capacity of the auditorium is 1,500.

Formerly the popular lecture tickets were sold to students for $1.00. Because of the auditorium's limited capacity, however, the Section now arranges to have all suitable lectures repeated at the high school. The Section negotiates with the speakers to present the talks at a low price, and the high-school authorities pay the speakers and collect a small fee from the students.

Competitions Encourage Technical and Popular Papers

Two local conventions are held each year by the Lynn Section, one for a technical paper competition and the other for presentation of papers on popular subjects.

Intended for young men who have not previously delivered papers before a national or District meeting, the technical paper competition is open to any national or local member under 35 years of age who has not previously won a first prize. Papers may be on any technical subject. Written papers are first graded by three judges and the eight best ones are selected, for presentation in 15-minute speeches at the first of the local conventions. Awards are made on the basis of 40 per cent for the written paper itself, 40 per cent for the oral presentation, and 20 per cent for the popular vote. Prizes for the winning papers are $15, $10, and $5.

The popular papers, presented at the second local convention, usually have to do with personal hobbies. The six best-written papers are selected for oral presentation and three prizes awarded. Last year an exhibit of color photography, a speech on a historical collection of stockings, and a ventriloquist act won the prizes.

About 100 people attended the technical paper contest and 500 the popular paper convention in 1938–39.

Movies Start Section Meetings. The plan of showing a short motion picture at the beginning of Section meetings has been adopted by the Philadelphia Section to increase interest and solve the problem of latecomers. Habitually tardy members only miss a part of the film and do not disturb the rest of the audience, whereas starting the meetings late to avoid having talks interrupted by late-comers seemed to annoy the more punctual. Films lasting about 15 or 20 minutes have been found most satisfactory. Usually technical or descriptive, the films are most often those distributed free by industrial companies, although some cartoons have been shown. In order to test the members' reaction to the use of movies, which is believed generally favorable, the program committee recently decided to omit films for a few meetings.

Students Entertained. Each month four members of the Los Angeles Section entertain four students, two from the University of Southern California and two from the California Institute of Technology. A list of prospective hosts has always been available since the practice began. Each student is asked to prepare a five-minute talk on any subject he chooses.

Branch • • • •

Branch Convention Held at Pratt Institute

The 14th annual convention of AIEE Student Branches in the New York City District (3) was held April 25, 1940, at Pratt Institute School of Science and Technology, Brooklyn, N. Y. In addition to seven local inspection trips and inspection of the Pratt Institute shops and laboratories, the convention program included a technical session at which the following student papers were scheduled:

AN ELECTRONIC D-C TRANSFORMER, **C. Conrad Dalman**, College of the City of New York

A HIGH-QUALITY BROADCAST RADIO RECEIVER, **William R. Hutchins**, Columbia University

MAPPING OF AN ELECTROSTATIC FIELD, **Laurence Bershad**, Polytechnic Institute of Brooklyn

CONSTANT POTENTIAL D-C POWER SUPPLY, **Harold F. Brown**, Pratt Institute

THE METHOD OF SELECTIVE REMOTE CONTROL BY AUDIO SIGNAL, **Stanton Shackell**, Rutgers University

AUTOMATIC SLIDE-BACK VACUUM VOLTMETER, **Philip Volz**, Newark College of Engineering

Awards for papers were made to: William R. Hutchins, first prize; Philip Volz, second prize; Stanton Shackell, honorable mention. The prizes were presented at a banquet at which featured speakers were Doctor C. F. Scott, professor emeritus, Yale University, and founder of AIEE Student Branches, and E. A. Baldwin, manager of Paris office and vice-president, International General Electric Company. Guests of honor included President F. Malcolm Farmer and National Secretary Henline of the AIEE. George A. Doxey, chairman of the Pratt Institute Branch, was chairman of the convention. Besides those represented on the technical program, the following Student Branches are included in District 3: Cooper Union Institute of Technology, New York, N. Y., Stevens Institute of Technology, Hoboken, N. J., University of Puerto Rico, San Juan.

Standards • • •

New Transformer Standards

A new set of proposed American standards and recommended practices for transformers, regulators, and reactors has just been completed by the sectional committee on transformers of the American Standards Association. The new standards with their appendixes will combine in one volume considerable new material on standards, testing, and operating guides for transformers. It is believed that this will be the most complete single publication of its kind ever compiled. In order to obtain comments and criticisms from the entire industry, these standards are now being published for a 12-month trial period as "Proposed American Standards and Recommended Practices for Trial and Study."

As so much of the material contained in

this proposed standard has already superseded in actual practice the provisions contained in the existing AIEE standards concerned, it has been decided to withdraw from circulation the following AIEE publications: No. 12, "Constant Current Transformers"; No. 13, "Transformers, Induction Regulators, and Reactors"; No. 14, "Instrument Transformers"; No. 100, "Recommendations for the Operation of Transformers"; and the Test Code for Transformers.

Outstanding provisions of the proposed standards include separation of the temperature rise from the ambient and total temperature in order to avoid confusion; establishment of standard impulse insulation levels; inclusion of enlarged guides for operation of transformers with (1) recognition that the name-plate rating and output are not necessarily the same; (2) a new section permitting short-time overloads for both emergency and recurrent conditions set up so that the values permitted will not shorten the life of the transformer; and (3) a change from 40 to 30 degrees centigrade in the average daily ambient temperature at which transformers may be operated continuously for long periods of time. It is possible that the new guides will permit greater outputs under the same service conditions than has been possible in the past. They do not change the rating of transformers for usual service conditions.

The sectional committee on transformers, which is made up of representatives from the AIEE, National Electrical Manufacturers' Association, Edison Electric Institute, Association of American Railroads, and the National Bureau of Standards, has been working for the past four years on these new standards.

In the past, standards for transformers, as well as for rotating machinery, have been devoted largely to setting up specifications for the general principles on which acceptance tests were based, in order that when tests made in accordance with these specifications were completed, the name-plate data for the transformer could be arrived at. To make these new standards more useful to the industry, a somewhat different arrangement of the material has been made, as follows.

The material consists of the standards and two appendixes. The standards are divided into seven sections: (1) definitions; (2) standards common to transformers, regulators, and reactors; (3) standards for distribution and power transformers; (4) standards for instrument transformers; (5) standards for constant-current transformers of the moving-coil type; (6) standards for induction and step-voltage regulators; (7) standards for current limiting reactors.

The two appendixes are: (1) test code for transformers and other induction apparatus; (2) guides for the operation of transformers in service.

The material included in the proposed standards and appendixes was based largely upon AIEE standards Nos. 12, 13, 14, and 100, the NEMA transformer standards, and the AIEE proposed test code for transformers.

The test code previously issued by the AIEE has been enlarged considerably and brought up to date. Complete instructions for making electrical tests are given, together with standard connections used in making heat runs. In cases where two or more methods of making tests or corrections are recognized (as, for instance, when correcting the no-load loss to a sine-wave basis) these methods are outlined in the code. The latest method of making impulse tests is included. The tests are specified by kilovolt instead of by "test gaps" which have been in general use since 1933.

In comparison with AIEE standards earlier than 1930, the new standards are more liberal, in that they recognize overloads which probably more than compensate for whatever restrictions might be imposed under some conditions by reducing the standard ambient from 40 degrees centigrade to a daily average of 30 degrees coupled with a maximum of 40 degrees. As mentioned before, it is possible with the new standards that a greater output may be delivered under the same service conditions. The new standards do not change the rating of transformers for usual service conditions.

This publication, which consists of 100 pages, may be ordered from AIEE headquarters, 33 West 39th Street, New York, N. Y., at a cost of 75 cents net. (The AIEE member discount does not apply.)

Co-ordination of Graphical Symbols. A real need for co-ordination of graphical symbols was pointed out by R. T. Henry at the March 26 standards committee meeting. The sectional committee on graphical symbols, *Z32*, under joint sponsorship of The American Society of Mechanical Engineers and AIEE has been struggling with this problem ever since its organization, but has not as yet found a way to eliminate symbol conflicts. One particular instance was cited—the same symbol is used for contactor and for capacitor. It was finally agreed to advise the sectional committee that the standards committee deprecates the adoption of any American standard containing conflicts in graphical symbols.

Air Switches and Bus Supports. At the March 26, 1940, meeting of the standards committee, K. B. McEachron, chairman of the committee on protective devices of the Institute, submitted a proposed revision of AIEE Standard No. 22. This revision, entitled "Standards for Air Switches and Bus Supports" will, after formal approval by the board of directors, be issued for a trial period of one year. By that time it is hoped it will be possible to add an impulse-test voltage and ten-second wet-test voltage on which complete agreement has not been reached as yet.

Co-ordinating Committee 6 Formed. Announcement was made at the March 26 meeting of the standards committee of the completion of the personnel of standards co-ordinating committee 6, on interference, sound, and noise problems. Members are:

R. G. McCurdy, Bell Telephone Laboratories, Inc., *chairman*; P. L. Alger, General Electric Company; W. F. Davidson, Consolidated Edison Company of New York, Inc.; R. D. Evans, Westinghouse Electric and Manufacturing Company; Gordon Thompson, Electrical Testing Laboratories.

Co-ordinating Committee 7 Planned. It was agreed at the March 26 meeting that standards co-ordinating committee 7 should be organized. This committee, personnel of which has not yet been determined, will cover the general field of conduction in vacuum, gases, solids, and liquids. The co-ordination of ratings of wire and conductors with the ratings of the apparatus they serve may be investigated, as well as such questions as the rating of fuses, circuit breakers, starting circuits, short and overtime ratings, flicker, etc. An exact outline of scope will be determined at a later date.

Electrical and Magnetic Magnitudes and Units. At the March 26 meeting of the standards committee, Professor E. Bennett, University of Wisconsin, was appointed to represent the Institute on the sectional committee on electrical and magnetic magnitudes and units, *C61*. This vacancy has existed since the death of Doctor A. E. Kennelly.

Storage Batteries. The chairmanship of the AIEE delegation on sectional committee *C40*, storage batteries, has been delegated to Harvey N. Stover, battery division, Philco Radio and Television Corporation. The other members of the delegation are C. J. Dempwolf, Carlile and Doughty, Inc., and Ralph Seabury, Delco-Remy division, General Motors Corporation.

Rotating Electrical Machinery. The chairmanship of the AIEE delegation on the sectional committee on rotating electrical machinery, project *C50*, has been delegated to Professor Reinhold Rudenberg, of Harvard University.

Personal • • •

D. C. Prince (A'16, F'26) formerly chief engineer, switchgear department, General Electric Company, Philadelphia, Pa., has been made manager of the commercial engineering department, with headquarters at Schenectady, N. Y. Born February 5, 1891, at Springfield, Ill., he received the degrees of bachelor of science (1912) and master of science (1913) in electrical engineering from the University of Illinois. Following graduation he spent a year with General Electric at Schenectady, as test man and on special problems. From 1914 to 1917 he was employed on valuations and rate-making by the Illinois State Public Utilities Commission, and from 1917 to 1919 was a first lieutenant in the ordnance department of the United States Army. He returned to General Electric in 1919, becoming a research engineer in the radio department in 1920. In 1923 he was assigned to the research laboratory, first on vacuum tube applications, and later as head of the power control section. He went to Philadelphia in 1929 as research engineer of the switchgear department, becoming chief engineer in 1931. He is at present a director of the Institute, a member of the committee on communication, and has been chairman of the Philadelphia Section.

T. H. Hogg (M'31, F'38) chairman and chief engineer of the Ontario Hydro-Electric Power Commission, Toronto, Ont., Can., has been elected president of the Engineering Institute of Canada. He was born April 20, 1884, at Chippawa, Ont., and received the degrees of bachelor of scientific arts in 1908 and of civil engineer in 1914 from the University of Toronto, which also awarded him the honorary degree of doctor of engineering in 1927. He was a member of the engineering staff of the Ontario Power Company, Niagara Falls, Ont., 1902–04, and in 1909 returned to the company as assistant designing engineer and superintendent of construction of the Salmon River development at Pulaski, N. Y. In 1911 he became editor of the *Canadian Engineer*. He went with the Ontario Hydro-Electric Power Commission in 1913 as assistant hydraulic engineer, becoming chief hydraulic engineer in 1924, chief engineer in charge of construction and operation in 1934, and chairman and chief engineer in 1937. He has also been consultant on power projects for the Canadian government and others.

F. B. Hynes (F'31) has been appointed chief engineer of Crocker-Wheeler Electric Manufacturing Company, Ampere, N. J., and will have charge of all engineering and research activities. Born June 16, 1891, he received the degree of mechanical engineer from Cornell University in 1910. He became associated with the Crocker-Wheeler company the same year as specification engineer, becoming successively assistant manager of the specification department, electrical designer on induction motors and alternators, and engineer estimator. In 1915 he was put in charge of engineering and cost estimating and motor applications; in 1918 he was made assistant chief engineer in charge of estimating; and in 1926 he became manager of the engineering department under the chief engineer. In 1930 he was made manager of engineering, in charge of engineering and policy, continuing in that position until his present appointment. He is also a member of the National Electrical Manufacturers' Association.

G. A. Hughes (A'17) has been elected chairman of the board of the Edison General Electric Appliance Company, Chicago, Ill. He had been president of the company since its formation in 1918. He was born April 14, 1871, and attended the University of Minnesota. From 1897 to 1908 he was general manager of the Hughes Electric Company, operating utility properties in North Dakota and Montana. In 1908–09 he was engaged as a manufacturer's agent for electrical apparatus in Chicago, and in 1910 he organized the Hughes Electric Heating Company, of which he was president. The company made and sold the Hughes electric range, which he had invented, until the formation of Edison General Electric in 1918. Mr. Hughes was recently named a "modern pioneer" by the National Association of Manufacturers (*EE, March 1940, p. 171*) for his inventions of heating units.

H. B. Waters (A'04) has been made president of the Telluride Power Company, Salt Lake City, Utah. He was formerly general manager of the company. Born July 19, 1879, he was graduated from the electrical course at Cornell University in 1903 with the degree of mechanical engineer. He was with the Missouri River Power Company in Montana 1903–05, and from 1905 to 1911 was in charge of the mechanical- and electrical-engineering departments of California Polytechnic School, San Luis Obispo, becoming vice-director of the school. In 1911 he became chief engineer for the Beaver River Power Company and Idaho Power and Light Company, later becoming general manager for the Beaver River company and the Southern Utah Power Company. He had been general manager of the Telluride company for over 20 years.

J. H. Gordon, Jr. (M'28) chief engineer, Long Island area, New York Telephone Company, has retired. Born at Washington, D. C., May 13, 1875, he attended Columbian University and Johns Hopkins University, graduating from the latter in 1896 as "proficient in electrical engineering". In 1927 he received the degree of bachelor of engineering from Johns Hopkins. He entered the employ of the New York Telephone Company in 1896, and was successively promoted to the positions of assistant traffic engineer (1901), traffic engineer (1907), superintendent of traffic (1914), assistant general traffic manager (1920). He had been chief engineer for the Long Island area since 1927.

L. L. Crump (M'32) formerly assistant chief engineer, James R. Kearney Corporation, St. Louis, Mo., has been made chief engineer. Born July 20, 1891, at Centralia, Mo., he received the degree of bachelor of science in electrical engineering from the University of Missouri in 1914. After a year as apprentice with the Emerson Electric Manufacturing Company, St. Louis, he became a construction engineer for the Union Electric Light and Power Company, St. Louis, in 1915, continuing with the company until 1930. He was a design engineer for W. N. Matthews Corporation, St. Louis, 1930–31, joining the Kearney company in 1931 as a design and sales engineer.

R. R. Robley (A'18, M'20) formerly superintendent of operations, Portland General Electric Company, Portland, Ore., has been appointed assistant to the vice-president. Born May 31, 1875, in Walla Walla County, Wash., he received the degree of electrical engineer from the University of Oregon in 1901. He was employed by California Gas and Electric Corporation, Santa Rosa, and Columbia Improvement Company, a Stone and Webster subsidiary, before going with Portland General Electric Company in 1904. He has been with the company continuously ever since.

H. P. Sedwick (M'32) has been appointed general manager of the Public Service Company of Northern Illinois, Chicago, Ill. A native (1893) of Arkansas, he studied electrical engineering at the University of Arkansas. He entered the employ of the Public Service Company of Northern Illinois in 1913 as assistant engineer, becoming district engineer in 1917, and district manager in 1921. He was appointed assistant to vice-president in charge of operations in 1923, and in 1933 was made general district manager, the title being changed in the same year to general division manager, in which position he continued until his present appointment.

E. S. McConnell (A'29, M'36) has returned to Anaconda Wire and Cable Company, Hastings-on-Hudson, N. Y., as electrical engineer, after leave of absence with the Copper Wire Engineering Association, Washington, D. C. For the past two years he had charge of field engineering service for the association in the south and east, especially in connection with the rural distribution projects sponsored by the Rural Electrification Administration. During the previous year he was in charge of the preparation of the association's sag and tension charts for overhead copper conductors.

W. H. Fenn (Enrolled Student) University of California, Berkeley, has been awarded one of eight Charles A. Coffin Fellowships granted for research during the academic year 1940–41. He holds the degrees of bachelor of science and master of science from the University of California, and will work there on the application of square-wave voltages to special problems, the production of high-frequency saw-tooth voltages, and their application to the cathode-ray study of ultrahigh-speed phenomena.

H. E. Mahan (A'28) formerly assistant manager in charge of engineering at the illuminating laboratory of the lighting division of General Electric Company, Schenectady, N. Y., has been named manager of the illuminating laboratory section of the division. He has been with the organization since 1910, and has been associated with exposition illumination at the Panama Pacific, Century of Progress, and Golden Gate International expositions.

Gano Dunn (A'91, F'12) president, J. G. White Engineering Corporation, New York, N. Y., has been awarded the Order of Honor and Merit by the government of the Republic of Haiti, for outstanding service in the economic upbuilding of the country. Doctor Dunn, who has received the Hoover and Edison medals and many other honors, was among those recently cited as "Modern Pioneers".

J. S. Moulton (A'22, M'27) who has been assistant to the vice-president and assistant general manager of Pacific Gas and Electric Company, San Francisco, Calif., since 1930, has been promoted to a position in the statistical and rate department, in connection with which he will make system studies and handle regulatory, rate, and valuation matters.

T. F. Barton (A'12, F'30) assistant manager of the New York district, General Electric Company, New York, N. Y., and a vice-president of the AIEE, has been elected third vice-president of the Electrical and Gas Association of New York, Inc. A biographical sketch of Mr. Barton appeared in the March issue, in connection with his nomination as a director of the Institute.

G. T. Shoemaker (M'20, F'39) who has been serving since 1938 as president of the United Light and Power Service Company, Kansas City, Mo., will return to his former position as vice-president of the Kansas City Power and Light Company. He has been associated in engineering and managerial capacities with the United Light and Power Company and its affiliates since 1913.

D. M. Simmons (A'22, F'28) formerly chief engineer, General Cable Corporation, New York, N. Y., has been made a vice-president of the organization as of March 20, 1940. He was recently appointed a director. A biographical sketch of Mr. Simmons appeared in the March issue, page 134.

C. L. Chatham (A'25, M'32) formerly assistant distribution engineer, electric distribution department, Public Service Electric and Gas Company, Newark, N. J., has been made assistant division superintendent of the Passaic division of the department, with headquarters at Paterson, N. J.

H. J. Gille (A'01, M'13) agricultural and industrial development manager, Puget Sound Power and Light Company, Seattle, Wash., has been elected president of the Associated Chambers of Commerce of Washington.

M. E. Lundberg (A'37) manager, Uintah Power and Light Company, Roosevelt, Utah, has been awarded for 1939 the gold key presented annually by the Junior Chamber of Commerce of that community to its outstanding civic leader.

C. C. Musgrove (A'36) who has been representative of the Dallas, Tex., territory for Pacific Electric Manufacturing Company, has been appointed representative for the state of Texas, except El Paso, and for the states of Oklahoma and Louisiana.

F. A. Rogers (A'06, M'28) dean of engineering, Lewis Institute, Chicago, Ill., has been nominated by the Western Society of Engineers to serve as a member of the Washington Award Commission for a three-year term.

G. H. Ikola (A'31) formerly engaged in electrical engineering for the Koppers Company, Pittsburgh, Pa., is now a layout designer for the Douglas Aircraft Company, Santa Monica, Calif.

Obituary • • •

Henry Hutchinson Norris (A'03, M'05, F'12) supervisor of personnel and special instruction, Boston Elevated Railway, Boston, Mass., died April 14, 1940. He was born April 26, 1873, at Philadelphia, Pa. He studied electrical engineering at Johns Hopkins University, where he received in 1894 a diploma as "proficient in electrical engineering," no engineering degree being given there at that time, and at Cornell University, where he received the degree of mechanical engineer in 1896. He was engaged in electrical work for various companies 1890–94. In 1896 he became an instructor in electrical engineering at Cornell University, Ithaca, N. Y., in 1901 assistant professor, in 1905 professor, and from 1909 to 1913 was head of the electrical engineering department. In 1913 he became associate editor of the *Electric Railway Journal*, McGraw-Hill Publishing Company, New York, N. Y., in 1921 managing editor, and in 1923 assistant to the president of the McGraw Hill company. A short time later he became educational advisor to the Boston Elevated Company, Boston, Mass., continuing with the company until his death. He was a manager of the Institute 1909–12, and was also a member of Tau Beta Pi, Sigma Xi, and the Society for Promotion of Engineering Education. In 1904 he was superintendent of tests for the Electric Railway Test Commission, member of the International Jury of Award, and secretary of the group on electrical machinery, at the St. Louis Exposition. He was author and co-author of several books and had written many articles for the technical press.

Hugh Denehy (A'12) assistant consulting electrical engineer, Central Mining and Investment Corporation, Johannesburg, Transvaal, South Africa, died February 21, 1940. He was born April 28, 1883, at Okla, India, and received his technical education at Dalwich College and Northampton Technical Institute, London, Eng. From 1902 to 1905, he was with the Electric Supply Company, Ltd., London, first as an articled pupil, and then as charge engineer. He was a substation engineer for the Metropolitan Railway Company, London, 1905–07. In 1907 he went to South Africa as mains engineer and testing electrician for the South African Railways, Durban, Natal, in 1910 becoming deputy power station engineer for the company. During the period 1908–1911 he was also a lecturer in electrotechnics at the Durban Technical Institute. In 1911 he became chief electrical engineer for the Robinson Gold Mining Company, Ltd., Johannesburg, and was subsequently associated as electrical or resident engineer with various other mining properties in the Transvaal, including the Transvaal Gold Mining Estates, Nourse Mines, Ltd., Modderfontein B Gold Mine and the Central Mining and Investment Corporation. He was also a member of The Institution of Electrical Engineers of Great Britain, the South African Institution of Engineers, South African Institute of Electrical Engineers, and other organizations.

Francis William Clements (A'08) retired chairman of the State Electricity Commission of Victoria, Melbourne, Australia, died December 12, 1939. He was born at Halstead, Essex, England, in 1864, and received his technical education at the City Guilds College, London. From 1881 to 1896 he was associated with the Brush Company, first as pupil and in the contracts department in London, later as representative in Manchester, Eng., and in Hungary, and as joint manager of factories and contract department in Vienna. In 1896 he became engineer and manager of the Bournemouth Electric Supply Company, in England, and in 1898 resident engineer for the County of London. He went to Melbourne, Australia, in 1899 as engineer and manager of the Electric Lighting and Traction Company of Australia, and local managing director and chief engineer of the Adelaide Electric Supply Company. He later became engineer and manager, then chief engineer, manager, and finally managing director and chief engineer of the Melbourne Electric Supply Company, Ltd. About ten years ago he was made a member of the State Electricity Commission of Victoria, and later became chairman of the Commission, continuing in that position until his retirement. He was also a member of the Institution of Electrical Engineers of Great Britain.

Walter Herman Graef (A'08, M'13) electrical contractor, Stapleton, N. Y., died February 20, 1940. He was born August 30, 1872, and studied at Stevens Institute of Technology. He was employed by General Electric Company from 1889 to 1892, first in the test course at Schenectady, N. Y., and later on repair work in New York. From 1893 to 1901 he was associated with the New York Quotation Company, New York and from 1901 to 1904 was with G. and O. Braniff and Company, Mexico City. In 1905 he went to Iquique, Chile, as electrical engineer with J. K. Robinson, agent for Westinghouse Electric and Manufacturing Company, and some years later became electrical engineer for the F. H. Walter Company, Rio de Janeiro, Brazil. He was later a commercial engineer for Westinghouse Electric International Company, Pittsburgh, Pa., before establishing his own business as electrical contractor at Stapleton, N. Y.

Leonard Cook (A'39) electrical instructor, Delgado Central Trades School, New Orleans, La., died recently, according to information just received at Institute headquarters. He was born September 25, 1875, at Clarksville, Tenn., and attended Kentucky Wesleyan College, receiving his technical training by correspondence. He had been engaged in electrical work since 1900, with the Tuggle Electric Company, Beaumont, Tex., 1900–03, and subsequently in New Orleans, being employed at various times by the Barnes Electric Company, National Automatic Fire Alarm Company, J. W. Richardson, National Automatic Electrical Supply Company, and others. From 1913 to 1916 he had his own electrical contracting business, and from 1917 to 1921 was an electrician at the United States Naval Station at New Orleans. He was foreman for the Phoenix Utilities Company 1922–24, and had held his position at the Delgado Central Trades School since 1924.

Paul O'Brien (A'24) assistant chief electrician, New York Hospital, New York, N. Y., died March 10, 1940. He was born August 22, 1901, at Paterson, N. J., and graduated from the New York Electrical School in 1924. In 1922–23 he was general manager of Frederick H. Pruden, Inc., radio firm, Jersey City, N. J., and the following year was employed by the Wappler Electric Company, New York, in the testing laboratory and on sales. In 1924 he became

electrician at the Manhattan Eye, Ear, and Throat Hospital, and following a period as partner in the Yorkville Engineering Company, New York, and as assistant engineer in the McAllister Hotel, Miami, Fla., and the George Washington Hotel, Jacksonville, Fla., he became chief electrician and second assistant engineer at that hospital. He had held his position at New York Hospital since 1932.

Michael A. Horan (A'29) assistant division superintendent, Public Service Electric and Gas Company, Paterson, N. J., died January 19, 1940. He was born May 3, 1886, at New York, N. Y., and educated there. From 1906 to 1915 he was employed by the New York Edison Company, New York, on subway work, in the meter department, and in the mapping and record bureau. Since 1915 he had been with Public Service Electric and Gas Company at Paterson, first engaged in inventory work, and later becoming field engineer, and in 1925 district superintendent. He had held the position of assistant division superintendent for several years.

Membership • •

Recommended for Transfer

The board of examiners, at its meeting on April 18, 1940, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Cory, M. M., professor of electrical engineering, Michigan State College, East Lansing.
Smith, W. L., professor emeritus of electrical engineering, Northeastern University, Boston, Mass.

2 to Grade of Fellow

To Grade of Member

Bailey, E. H., district transformer specialist, General Electric Company, Atlanta, Ga.
Baughn, E., assistant engineer, The Washington Water Power Company, Spokane.
Bruce, R., general superintendent, Memphis Generating Company, Memphis, Tenn.
Calabrese, G., assistant engineer, Consolidated Edison Company of New York, Inc., New York, N. Y.
Davis, J. A., general superintendent, Mesilla Valley Electric Company, Las Cruces, N. Mex.
Denkhaus, W. F., staff engineer, The Bell Telephone Company of Pennsylvania, Philadelphia.
Gross, E. T. B., resident doctor, Cornell University, Ithaca, N. Y.
Herskind, C. C., electrical engineer, General Electric Company, Schenectady, N. Y.
Lovell, T. J., electrical engineer, United States Bureau of Reclamation, Denver, Colo.
Meador, J. R., electrical engineer, General Electric Company, Pittsfield, Mass.
Meagher, J. J., junior engineer, New York and Queens Electric Light and Power Company, Flushing, N. Y.
Mittanck, E. H., engineer, Southwestern Bell Telephone Company, Dallas, Tex.
Rapport, A. H., instructor in electrical engineering, College of the City of New York, New York, N. Y.
Roy, J. J. S., senior electrical engineer, Bureau of Ordnance Navy Department, Washington, D.C.
Shepherd, J. O'D., cost studies engineer, Southern Bell Telephone and Telegraph Company, Atlanta, Ga.
Simpson, W. L., chief electrical engineer, Cia. Carris, Luz & Forca, Rio de Janeiro, Ltd., Brazil.
Snedeker, C. F., assistant engineer, Consolidated Edison Company of New York, Inc., New York N. Y.
Stanley, C. M., Partner, Stanley Engineering Company, Muscatine, Iowa.
Strasbourger, J. C., system load dispatcher, Cleveland Electric Illuminating Company, Cleveland, Ohio.
Taylor, A. Y., consulting engineer, A. Y. Taylor and Company, Clayton, Mo.
Tomlinson, C. M., senior staff engineer, Bell Telephone Company of Pennsylvania, Philadelphia.
Wheeler, K. L., electrical engineer, Cleveland Electric Illuminating Company, Cleveland, Ohio.

23 to Grade of Member.

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Names of applicants in the United States and Canada are arranged by geographical Districts. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before May 31, 1940 or July 31, 1940, if the applicant resides outside of the United States or Canada.

United States and Canada

1. North Eastern

Anderson, C. R., 424 Greenwood Place, Syracuse, N. Y.
Chase, L. P., H. E. Stockwell Company, Boston, Mass.
Field, R. F. (Member), General Radio Company, Cambridge, Mass.
Lapinski, C. S., Manning, Maxwell and Moore, Inc., Bridgeport, Conn.
Lind, L. L., Jr., Narragansett Electric Company, Providence, R. I.
McAllister, J. F., General Electric Company, Schenectady, N. Y.
Newquist, R. R., Allis-Chalmers Manufacturing Company, Boston, Mass.
Palmer, A. M., Trumbull Electric Manufacturing Company, Plainville, Conn.
Ryan, J. F. (Member), Eastman Kodak Company, Rochester, N. Y.
Sharp, D. D., Hygrade Sylvania Corporation, Salem, Mass.
Sherry, W. H., J. H. Williams and Company, Buffalo, N. Y.
Summerville, A. O. (Member), Malden Electric Company, Malden, Mass.
Watson, B. F., Massachusetts Institute of Technology, Cambridge.

2. Middle Eastern

Baehr, A. M., 1400 West 25th Street, Cleveland, Ohio.
Bender, J. A., Cleveland Electric Illuminating Company, Cleveland, Ohio.
Benedict, P. R., Westinghouse Electric and Manufacturing Company, Philadelphia, Pa.
Booth, J. D., Westinghouse Electric and Manufacturing Company, Baltimore, Md.
Bowen, P. E., Bell Telephone Company of Pennsylvania, Philadelphia.
Craven, C. L. (Member), Bell Telephone Company of Pennsylvania, Philadelphia.
Cunningham, R. M., Bell Telephone Company of Pennsylvania, Philadelphia.
Dunlap, J. D., Brown Instrument Company, Philadelphia, Pa.
Falkenwald, C. O., Rural Electrification Administration, Washington, D. C.
Farris, W. A., United States Engineer's Office, Cincinnati, Ohio.
Fonda, B. P. (Member), Fonda and Warfield, Baltimore, Md.
Graff, R. W., Philadelphia Electric Company, Springfield, Pa.
Hickok, R. D., Jr., Hickok Electrical Instrument Company, Cleveland, Ohio.
Hollenback, W. L., Hollenback's Radio Supply, Altoona, Pa.
Horstman, C. C., Westinghouse Electric and Manufacturing Company, Sharon, Pa.
Lehman, L. G. (Member), University of Pittsburgh, Pittsburgh, Pa.
Mason, R. B., Edward G. Budd Manufacturing Company, Philadelphia, Pa.
Mowery, J. R., Jr., DeWalt Products Corporation, Lancaster, Pa.
Nobles, C. R., Westinghouse Electric and Manufacturing Company, Baltimore, Md.
Opitz, F. M., Consolidated Gas Electric Light and Power Company, Baltimore, Md.
Pierce, R. M., The WGAR Broadcasting Company, Cleveland, Ohio.
Salconi, P. C., Consolidated Gas Electric Light and Power Company of Baltimore, Baltimore, Md.
Schwalb, Hickok Electrical Instruments, Inc., Cleveland, Ohio.
Walters, F. S., Potomac Electric Power Company, Washington, D. C.
Wolff, H. G., United States Government Aircraft Radio Laboratory, Dayton, Ohio.
Wood, W. H., Bell Telephone Company of Pennsylvania, Philadelphia.

3. New York City

Bieling, C. A., Bell Telephone Laboratories, Inc., New York, N. Y.
Carmody, H. A., New York and Queens Electric Light Power Company, Long Island City, N.Y.
Cary, F. L., Consolidated Edison Company of New York, Inc., New York, N. Y.
Koepp, H. A., Western Electric Company, Inc., Kearny, N. J.
Parsons, H. E., Board of Transportation, New York, N. Y.
Weiser, B. M., Scientific Illumination, New York, N. Y.
Wenson, H. W., Board of Transportation, New York, N. Y.

4. Southern

Allen, A. C., Wagner Electric Corporation, Memphis, Tenn.
Beville, J. W., Jr., Florida Power and Light Company, Miami.
Davis, N. E., Georgia Public Service Commission, Atlanta.
Dibble, G. L., Jr., Alabama Power Company, Birmingham.
Finnegan, J. H., United States Navy, Norfolk Navy Yard, Portsmouth, Va.
Gilmer, B. S., Southern Bell Telephone and Telegraph Company, Atlanta, Ga.
Goers, H. J., Aluminum Company of America, Atlanta, Ga.
Leland, W. B., Burlington Mills Corporation, Greensboro, N. C.
Litman, S. W., University of South Carolina, Columbia.
Rader, J. F. (Member), South Carolina Electric and Gas Company, Columbia.
Webb, A. L., Florida Power and Light Company, Miami.
Wilson, M. D., Kentucky-Tennessee Light and Power Company, Bowling Green, Ky.
Wood, A. P. (Member), Louisiana Public Utilities Company, Inc., Franklinton.

5. Great Lakes

Coffin, A. L., Federal Power Commission, Chicago, Ill.
Cox, E. B., Iowa Power Company, Champaign, Ill.
Cutler, B. H. (Member), The L. E. Myers Company, Chicago, Ill.
Dutton, W. C., Allis-Chalmers Company, West Allis, Wis.
Hatch, W. H., Public Service Company of Northern Illinois, Chicago, Ill.
Hazen, D. F., Illinois Iowa Power Company, Champaign, Ill.
Kuether, A. W., Kewaunee Manufacturing Company, Kewaunee, Wis.
Neighbours, R., Commonwealth and Southern Corporation, Jackson, Mich.
Stewart, J. W., Westinghouse Electric and Manufacturing Company, Milwaukee, Wis.
Zimmerman, H. R. (Member), Carnegie Illinois Steel Corporation, Gary, Ind.

6. North Central

Luton, M., Lights and Water Department, Gillette, Wyo.
Porter, E. C. (Member), Rocky Mountain Engineering Company, Denver, Colo.

7. South West

Ezell, A. D., Sun Oil Company, Beaumont, Tex.
Metz, O. F. (Member), Allis-Chalmers Manufacturing Company, El Paso, Tex.
Raudenbush, C., Jefferson College, St. Louis, Mo.
Roth, H. H., Allis-Chalmers Manufacturing Company, El Paso, Tex.
Schoonover, C. E., General Electric Company, Wichita, Kans.
Zalmanzig, F. D., San Antonio Public Service Company, San Antonio, Tex.

8. Pacific

Griffin, E. R., Recordall Manufacturing Company, Inc., Los Angeles, Calif.
Guyton, M. E., Pacific Electric Manufacturing Corporation, San Francisco, Calif.
Hart, C. M., Citizens Utilities Company, Kingman, Ariz.
Hatch, J. A., Corps of Engineers, United States Army, Camp Ord, Calif.
Noller, G. W., Underwriters' Laboratories, Inc., San Francisco, Calif.
Sabin, C. J., Phelps Dodge Mines, Bisbee, Ariz.

9. North West

Bryant, W. H., 756 North 81, Seattle, Wash.
Davis, C. R., Montana Power Company, Butte.
Gruber, A., Washington Water Power Company, Spokane.
Klehm, H. I., Washington Water Power Company, Spokane.
Norris, W. V. (Member), University of Oregon, Eugene.
Smith, T. T. (Member), United States Department of Interior, Portland, Ore.

10. Canada

Cowie, N. C., Great Lakes Power Company, Ltd., Sault Sainte Marie, Ont.
Girdwood, A. J., Canadian General Electric Company, Peterborough, Ont.
Goold, C. C. (Member), Bruck Silk Mills, Ltd., Cowansville, Que.
Knowles, G., Canadian Telephones and Supplies, Ltd., Vancouver, B. C.
Mills, F. P., Rolph Clark Stone, Ltd., Toronto, Ont.

Total, United States and Canada, 94

Elsewhere

Chadda, N. S., Jullundur Electric Supply Company, Ltd., Jullundur, Punjab, India.
Das Kalra, R., Lahore Electric Supply Company, Ltd., Lahore, India.
Jeans, A. E. (Member), Electricity Supply Offices, London, W. 4, England.
Mohtadi, M., care Anglo-Iranian Oil Company, Sunbury-on-Thames, England.
Selhi, A. S., B. P. Oil Mills, Agra, India.
Smith, R. (Member), Treasury Department, Monrovia, Liberia, Africa.
Trivedi, H. M., Callender's Cable and Construction Company, Ltd., Ahmedabad, India.

Total, elsewhere, 7

Transactions

Preprint of Papers and Discussions Comprising Pages 257–390 of the 1940 Volume

Some Recent Developments in Impulse-Voltage Testing

C. M. FOUST
MEMBER AIEE

N. ROHATS
ASSOCIATE AIEE

Synopsis: Impulse-voltage testing of electrical apparatus and circuits is a steadily growing practice and constant attention is therefore being given to improvements in testing methods. Accordingly, as progress is made it is necessary to describe recent changes. This paper presents a brief discussion of the present situation, describes some improvements in technique of surge analysis of apparatus and circuits, and in equipment for the generation and measurement of test surges.

EQUIPMENT and methods for impulse-voltage testing of apparatus and circuits have been added to and improved considerably within recent years. In comparison with the older methods, the newest technique provides for several important advantages. A decidedly better understanding of the surge mechanism of the circuit and an improved control of shape and timing of generated surges is now realized. Impulse-voltage tests and investigations are conducted with greater speed and reduced uncertainties.

The Twofold Nature of the Surge-Strength Problem

Impulse-voltage testing in its earliest period consisted in applying a surge voltage, measured for amplitude by the sphere gap, to the apparatus or circuit under investigation and watching for visible evidences of failure. The introduction of the cathode-ray oscillograph,[1] which provided for the recording of voltage wave shapes, opened the way to a more precise understanding of surge performance of circuits and strength of insulation.

At present a complete experimental analysis of the electric impulse or surge characteristic of an electrical machine or circuit will involve two general considerations. These are the surge mechanism of the circuit and the electrical strength of the circuit. Stated in a different way, any experimental analysis of the surge characteristics of a circuit, whether it is a machine winding or a connecting network, must, to be at all complete, answer two questions:

1. What is the nature of the current and voltage variations in the several parts of the circuit under surge conditions?
2. What is the strength of the circuit (insulation particularly) under surge conditions?

As an example, take the case of the rotating-machine winding where entering surges are subject to varied reflections and attenuations. Depending upon such factors as winding length, coil turn distribution, and terminal connections, voltage wave shapes and amplitudes inside the winding will vary widely particularly when the applied surge voltages are relatively short in time duration compared to the electrical length of the winding. To apply an impulse voltage, therefore, in such a case, to test for insulation strength, without an understanding of the surge mechanism involved, may frequently lead to incorrect results. The case of the rotating machine, however, is but one example of the many cases where in an experimental analysis both the surge mechanism and electrical strength of the circuit must be considered.

Oscillograph Electric-Transient Analyzer

Recognizing the importance of providing a measuring instrument for surge analysis which eliminated the delays and difficulties involved in the use of the single-discharge surge generator and high-speed cathode-ray oscillograph, the oscillograph electric-transient analyzer[2] was developed. Several years' use of this instrument has demonstrated its wide applications and has resulted in improvements in the device.

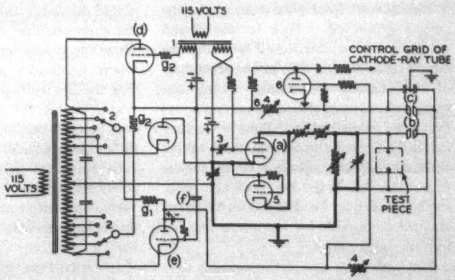

Figure 1. Oscillograph electric-transient analyzer

The oscillograph electric-transient analyzer generates a succession of low-voltage impulses of controlled wave shape for application to the circuit or apparatus to be analyzed for surge mechanism. The time of occurrence of the impulse waves is co-ordinated exactly with the time axis of a cathode-ray oscillograph and there is, therefore, an exact retracing of the wave image on the oscillograph screen. By connecting the deflection plate terminals to a selected point of the circuit under study the wave shape at this point is observed as a standing wave. By moving

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1. For all numbered references, see list at end of paper.

the deflection plate terminal rapidly through succeeding points on the test circuit, the travel of voltage wave shape along the circuit is made visible.

Figure 1 is the connection diagram for the latest analyzer. The circuit changes recently made are noted by numbers as follows:

1. Initiating transformer
2. Time-axis position control
3. Preliminary zero-line control
4. Balanced voltage time-axis circuit
5. Reverse-current tube
6. Cathode-beam control

The low-voltage surge-generator circuit shown in heavy lines produces a surge of adjusted shape for each cycle of the 60-cycle supply voltage. The surge is initiated by the firing of the thyratron tube *a* which in this circuit replaces the sphere gap of the high-voltage surge generator. The surge voltages are applied to the test piece and to the vertical deflection plates of the cathode-ray oscillograph *b*. Now the time axis of the oscillograph which is provided by the horizontal deflection plates *c* must have a correct and fixed time relation to the surges generated. This it was found could best be accomplished by firing the time-axis thyratron *d* from one secondary of the peaking transformer 1 and the surge tube *a* from the other secondary of the same transformer. Tube *d* in turn instantly fires the other time axis tube *e* through coupling capacitor *f*. By means of a capacitor 3 the firing of the surge thyratron *a* may be delayed any desired amount to provide for some zero line before the surge starts.

Most effective use of the cathode-ray-tube screen requires that the time axis begin at a point near the left edge of the screen and sweep to the right. To provide for the beam starting at the left a definite deflection voltage is required. Obtaining this from batteries or fixed-pole magnets has disadvantages. For the analyzer circuit, therefore, a portion of the 60-cycle voltage of the main transformer was utilized. Tap switches at 2 were found convenient for selecting the required beam bias voltage so that at the instant of beam initiation the bias would be correct. Resistors g_1 and g_2 absorb the transformer voltage when thyratron tubes *e* and *d* are tripped.

In the original analyzer the time-axis voltage was supplied through a single tube to one time-axis deflection plate, the other plate being grounded. This was found to have two disadvantages. It prevented good focusing of the cathode beam throughout its travel and it gave a converging deflection sensitivity (direct-voltage lines were not parallel). By using the balanced circuit as shown in figure 1 comprising principally tubes *d* and *e* and in which the time-axis plates have at each instant the same potential but of opposite polarity, these two disadvantages have been eliminated.

For the unidirectional polarity surges a single discharge tube at *a* was shown in the early analyzer circuit to be adequate. However, a number of instances occurred where oscillatory surges were required. For the low voltages utilized in the generator circuit the substitution of a gap was objectionable because of timing difficulties. In addition another discharge tube connected oppositely, as shown at 5, provided for the conduction of the reversed polarity currents accompanying oscillatory discharges of the main capacitor.

In view of preventing undesirable illumination on the cathode-tube screen and back-sweeping of the beam, a good arrangement for beam initiation and cutoff is required. This has been realized by taking off the time-axis circuit at the point marked 6 a positive-polarity voltage which is in part applied to the control grid of the cathode tube as shown in figure 2 and discussed in connection with the cathode-ray oscillograph in a subsequent section.

While the duration of the beam could be controlled by varying the time constant of the initiating circuit, better results are obtained by making the time constant longer than the slowest time axis and cutting off the initiating potential with a thyratron 6. The grid of this thyratron is connected to both sides of the time-axis circuit by resistors of such value that the grid potential becomes positive and fires the tube at the end of the time axis.

Surge Test of Insulation Strength

Surge-voltage and impulse tests of apparatus and conductor insulation are made with a surge generator, cathode-ray oscillograph and voltage divider, and sphere gap. As regards the generator and oscillograph, recent changes require some explanations.

Cathode-Ray Oscillograph

Some two years ago[3] there was described for the first time a practical high-speed oscillograph which dispensed with vacuum-pumping equipment and permitted simultaneous visual observation and recording of short-time surges. Complete circuit diagrams were presented. Continuous use of this oscillograph on a wide variety of work since then has resulted in many valuable refinements in equipment and methods. The following paragraphs describe the major changes adopted.

The diagram of figure 2 shows the latest arrangement of the control and timing parts and connections for the impulse generator-cathode ray oscillograph circuit. Apparatus and circuit changes are summarized as follows.

A. Substitution of an impulse transformer for an intermediate surge-generator unit.

B. Introduction of a special wave-front circuit giving extra timing precision.

C. More precise beam-duration control.

D. Introduction of extra light shielding for camera compartment.

E. Utilization of higher-speed camera.

In all high-speed cathode-ray-oscillograph work and particularly with non-recurring transients the problem of properly timing the oscillograph operation with the event to be recorded is an important one. In general impulse testing

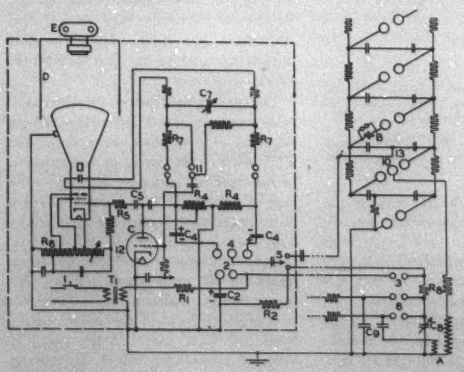

Figure 2. Impulse-generator and oscillograph control circuits

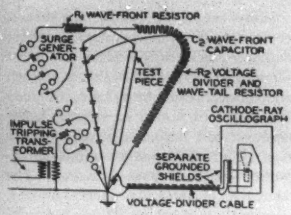

Figure 3. Schematic arrangement of surge-generator circuits

the total duration of commonly used time axes ranges from 1 to 100 microseconds. For full-time flashover on a standard wave such as th e1½x40 microsecond suitable time axes range from 50 to 100 microseconds and for the 1x5 wave from 5 to 10 microseconds. For some volt-time flashover curves and for wave-front work, time axes of total duration as low as 1 microsecond are sometimes required. For best results a short-time zero-deflection axis is required prior to the beginning of the recorded transient. For full-time flashover work with a 50-microsecond time axis, this zero-deflection time axis will be several microseconds long. Adequate time co-ordination between the time axis and the transient will be within one or two microseconds. However, for wave-front testing the zero-deflection time axis will be less than a microsecond and adequate time co-ordination will require a precision within tenths of a microsecond. For this reason a particular connection arrangement is used for full-time flashover work and a second connection for wave-front work. Changing from one connection to the other is accomplished by reversing the switch S on figure 2.

For full-time flashover tests S is turned down. The initiating switch 1 when closed provides for a power frequency voltage on the right sphere of gap 2 of the initiating surge circuit. As the left sphere already has on it a continuous voltage of positive polarity, this gap breaks down and is immediately followed by the breakdown of gap 3. Gaps 2 and 3 are in series and really constitute a three-electrode gap. They have been separated as shown so that the ultraviolet radiation from gap 2 will irradiate gap 4 and gap 3 will irradiate gap 8. Gaps 3 and 8 in turn are placed so as to irradiate the main-generator trip gap 10. Such irradiation produces ionization in the gaps so that they spark-over without delay when the potential on them reaches the spark-over value.

The voltage of capacitor C_9 is now applied across resistor R_2 through the switch S to the midsphere of the time-axis-circuit gap 4. Capacitor voltages C_4 are applied across resistors R_4 and a square-wave positive-polarity voltage is applied to the biasing grid of the cathode tube through R_4. This positive voltage is sufficient to reduce the negative blocking grid bias obtained from the main cathode excitation resistor R_4. The cathode beam is initiated and begins to deflect immediately in accordance with the time-axis voltage of capacitor C_7 which is charging from capacitors C_4 through resistors R_7.

Meanwhile the voltage across resistor R_3 is also across resistor R_8 and capacitor C_8. When the voltage C_8 rises to a predetermined value gaps 8 break down throwing capacitor voltage C_9 on the primary of the impulse transformer A. The resistance-capacitance product R_8C_8 is adjusted to give the required time interval between the beginning of the time axis and the transient excitation of the impulse transformer. The voltage wave on the secondary of the transformer is applied to the mid sphere of the three-electrode gap of the surge generator 10 and precipitates this gap breakdown which is immediately followed by breakdown of the remaining gaps of the Marx circuit and the production of the required surge voltage.

The impulse transformer is an air-core transformer of the type commonly used on damped-wave oscillators. Such a transformer has been found by experience to provide a simple, economical intermediate unit to replace the complete small-scale rectifying-type surge generator commonly used for this purpose. In view of the limited energy output of the transformer, best results are obtained if it is installed at the base of the surge generator and capacitance values are kept low to provide as square a voltage wave as possible. Returning now to the cathode-beam control, a circuit connected to and controlled by the sweep voltage is used to cut off the cathode beam after it has moved off the tube screen. Gap 11 is set to break down when the sweep voltage reaches a value high enough to complete the time axis and in so doing energizes the grid of thyratron 12 positively, causing it to fire and to short circuit the positive cathode-tube grid bias from the sweep circuit used to initiate and hold the cathode beam on. The cathode-tube grid immediately goes back to its negative polarity bias obtained from R_6 and the sequence of events is completed.

As the above described time-co-ordination mechanism is not adapted to split microsecond timing precision, a different technique is used for time axes of very short duration.

When switch S is turned up pressing control button S_1 breaks down gaps 2, 3, and 8 in order and finally gap 10 through the impulse transformer. As yet the oscillograph has not started. Experimentally it has been determined that the insertion of a low resistance at B in the surge generator circuit will provide sufficient delay in the breakdown of the Marx circuit gaps to permit the tripping of the sweep circuit gap 4 and the completion of the entire mechanism of cathode-beam initiation and initial zero-deflection sweep through a connection at 13 on the second stage of the surge generator. This arrangement provides for all the precision required in timing, succeeding surges occurring within 0.1 microsecond on the time-axis scale. The resistance B is bridged by a gap which breaks down to carry the main discharge current of the surge generator.

Surge-Generation Circuits

Recent increasing use of wave-front tests wherein time elements to be measured range as low as 0.1 microsecond at high voltage and 0.02 microsecond at low voltage have necessitated that more attention be given to the arrangement of surge-generator discharge circuits to eliminate spurious oscillations. Experience has gradually shown that the general considerations for reasonably smooth waves are as follows:

1. The ground point of the surge generator, oscillograph, test piece, and resistance voltage divider to converge as nearly as possible to one point as shown on figure 3.
2. The cable from the resistance divider to the oscillograph to be out of the generator field.
3. The oscillograph to be housed in shielded room and this room to be as well out of the field of the generator as possible.
4. The ground point to be as directly connected to good ground earth as possible, a few feet (less than ten) if possible.
5. Both ends of the divider cable to be terminated by a resistance equal to the surge impedance.
6. Several hundred ohms damping resistance in the deflection leads.

In figure 3 are illustrated several of these points. The diagram is not intended to show relative positions of apparatus as these are invariably peculiar to each installation. The practice of converging all ground connections at one point has been found to eliminate stray potentials in any one circuit due to the

ground connection of that circuit carrying ground current for another circuit. This has been shown to be important particularly in connection with the measurement circuit to the oscillograph.

A frequent source of disturbance in the measurement circuit is an oscillation resulting from the stray-capacitance coupling of high-voltage elements with the divider cable sheath. This can be eliminated by a shield as shown in figure 3 or by running the cable under the ground-floor level. If the oscillograph housing is located in the field of the high-voltage elements, local oscillations may occur in it for each surge-generator discharge. A separately grounded shield over the housing is therefore beneficial.

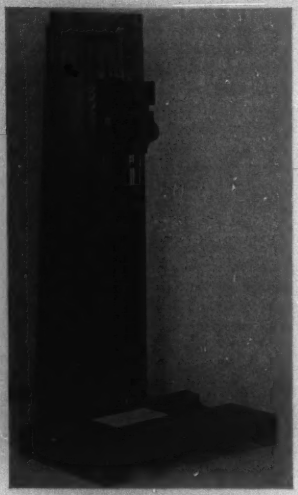

Figure 4. Projector for reproduction and analysis of cathode-ray-oscillograph film

A most important feature is a good short ground connection between the common point and ground. In fact, for high-voltage unbalanced discharge circuits, whether or not satisfactory short-time tests can be obtained will depend upon grounding conditions.

The resistance equal to the surge impedance at the oscillograph cable end provides for the elimination of reflections. This resistance should be carefully adjusted. However, experience has been that complete elimination of reflections is difficult. The resistor at the generator end of the cable is therefore advantageous as it provides against repeated reflections appearing at the oscillograph end.

Film Records

The high-vacuum type of oscillograph permits records of any size desirable depending upon the camera used. Experience however, has been that standard 35-millimeter records are most convenient and accurate. As each wave is observed visually, as it is recorded photographically, qualitative results are known before films are developed. With the small film records which can be dried in less than ten minutes after washing, inserted in a standard projector as shown in figure 4, the wave shape is projected on the lower table surface which is provided with cross-section lines. Direct calibrations are first made by projecting the calibration oscillogram. This provides a ratio of kilovolts per millimeter deflection which can be used repeatedly for the measurement of test oscillograms.

When film reproductions are required, and these usually necessitate some marking such as identifying numbers or scale division values, the wave image from the projector is transmitted through a transparent surface just above the table level. Such markings as necessary are made on this surface which a quick-drying ink. An unexposed film is inserted under this transparent surface and the image of the wave shapes and markings recorded usually at five times the size of the original negative. As this enlargement is really a positive film, prints from it will be as desired—black traces on a white background. Any number of paper-print reproductions are now made from this positive film without hazard to the original record.

Detection and Location of Faults

Because impulse tests involve voltage applications of only a few microseconds time duration, it is often difficult to know when failure has occurred or damage has been done to the test specimen. Especially is it important to know this immediately on application of a surge so that testing may be discontinued until the location or nature of the failure is determined. The most common and practical evidences of failure or damage are as follows:

1. Visible external arcs and corona streamers.
2. Excessive noise in the discharge.
3. Chopping or distortion of the oscillogram.
4. In oil-immersed apparatus, rising gas or smoke bubbles.
5. Indications of excessive current in the test leads.

Visible external arcs and corona streamers are present in most cases of insulator flashover such as porcelain insulators when tested for full-time flashover, or when volt-time curves are being taken. Corona streamers are visible at voltages below flashover and beginning usually on the rising front of the wave continue in extension as the voltage increases. The formation of these streamers, however, apparently lags behind the applied voltage and their extension continues for a time along with the dropping voltage of the wave tail. If the level of voltage of the wave is sufficiently high, these streamers bridge across the insulation and culminate in flashover. The critical

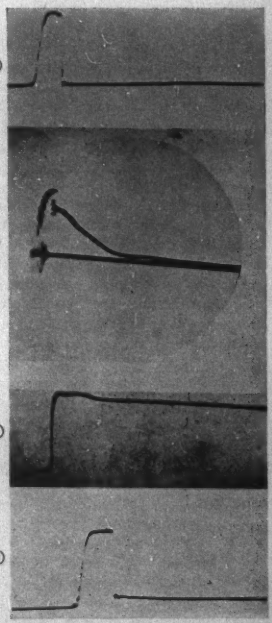

Figure 5. Sample oscillograms of insulation failure

A—Insulation failure on a wave tail showing the complete chopping obtained in a low-resistance breakdown

B—Insulation failure on a wave crest showing partial chopping obtained in a high-resistance breakdown

C—Partial insulation failure of a high-voltage cable as indicated by wave distortion on the crest

D—Complete insulation failure of a high-voltage cable on the next application following C

flashover is that of the lowest voltage level (crest voltage) which will complete flashover for about half the impulse applications. No difficulty is experienced in detecting flashover in such cases. Both visible flashover arcs and excessive noise give ample evidence of it. The flashover path shows the failure channel if the observer is watching the test piece carefully.

On wave-front tests, however, and for some cases of chopped waves additional difficulties are encountered. The chopping of the wave adds a volume of noise which renders this method of no value as an indicator, and distorts the test wave so that the oscillogram of the chopped wave cannot be used with any degree of certainty to indicate test-piece failure. It is always necessary to follow up the chopped wave with a full wave of the same voltage level. The full wave of a specified voltage level has a crest voltage 15 per cent lower than in chopped waves.

Chopping or distortion of oscillograms in full-wave tests are the most practical and certain indications of damage to the insulation under test. A sharp drop in the wave such as shown in figure 5*A* definitely shows that failure has occurred. This is the record of a failure in an air-insulated instrument transformer which could not have been detected by outside evidences or by excessive noise. This failure occurred from line-to-ground and took the form of a very low impedance

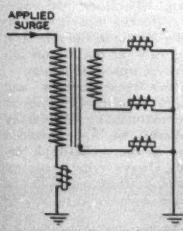

Figure 6. Arrangement of magnetic links for location of failure points

failure path. Figure 5*B* shows a distorted wave indicating partial failure.

Figure 5*C* is an unusual and interesting oscillogram of a cable failure showing a wave distortion due to partial failure on the surge preceding the one causing final breakdown, which is shown in figure 5*D*. Such records are not frequently obtained and their occasional occurrence stimulates confidence in the oscillograph.

Observation of the oil surface in oil-immersed apparatus sometimes is helpful in detecting and locating a failure, but in general is a very unsatisfactory method because small failures which can be detected from the oscillogram often do not result in rising bubbles, which can be seen on the surface of the oil.

In all these records the chopping and distortion of applied full waves are immediately observed on the screen of the high-vacuum oscillograph.[1] Although not infallible the oscillograph is the best evidence of damage. Simultaneous visual and photographic recording of the voltage wave shape across the test piece insures the detection of failures immediately. Time lost in testing and resulting confusion when surges are applied after the first failure can be avoided when each test-piece voltage wave can be observed as it is applied.

In many cases of impulse-voltage testing the test piece is made up of a number of parts such as several windings and possibly a core and a case. The most common practice is to apply the impulse to one winding with other windings and core and case grounded. It is always important to know when failure occurs just which insulation has been broken down. Particularly in connection with instrument transformers the authors have made many successful uses of the surge-crest-ammeter magnetic-link technique[4] commonly used for lightning measurements.

If as shown in figure 6 the connecting leads to the several parts of the test piece are brought through magnetic-link stations, the links can be used to indicate where breakdown occurs. As soon as the oscillograph indicates breakdown by chopping or distortion of the wave, the magnetic links are measured for residual magnetization in the surge-crest ammeter. If properly adjusted the magnetic links in the path of the failure current will receive greater magnetization.

Small coils such as shown in the figure have been used most commonly for this application. Two, three, six, or ten turns are used. The calibration curves for unidirectional surges are shown in figure 7. Depending upon the characteristics of the surge-generator circuit and the shape of the wave applied, the coils will carry normal capacitance current which increases in amplitude with applied voltage. Therefore, the magnetic link coils must be chosen to leave no link magnetization for these charging currents, but to provide sufficient turns to give measurable residual for the short-circuit currents.

Oscillographic Recording of Voltages Between Tap Points

While the greater portion of impulse testing is concerned with voltages between high-potential tap points and ground in

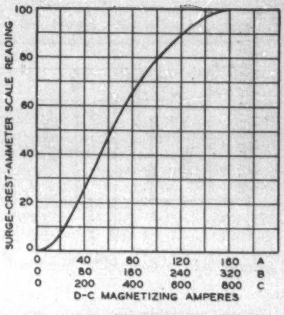

Figure 7. Surge-crest-ammeter magnetic-link calibration

A—Ten-turn coil
B—Five-turn coil
C—Two-turn coil

very many cases direct tap-to-tap voltage increments are required. This requirement calls for the measurement of low-voltage increments at high-voltage levels. With the deflection plates of the oscillograph either directly connected or through resistance or capacitance dividers, both plates become of the same voltage polarity. When the voltage between plates is sufficiently high for a suitable deflection, the absolute potentials of the plate will be excessive for good oscillograph operation, that is, absolute deflection-plate voltage will introduce a cathode-beam distortion which results in beam defocus and unsatisfactory records.

Until recently such tap-to-tap voltages have been obtained by subtracting tap-to-ground records or by accepting usually with considerable uncertainty such tap-to-tap records as could be obtained with minimum defects. The method of subtracting tap-to-ground measurements is unsatisfactory because of possible uncertainty in the timing of the two records, a point on which the actual values of tap-to-tap voltages depend.

Through the work of the authors marked progress has been recently made on this problem. A circuit has been built and tested which automatically does the subtracting of the two tap-point waves. Figure 8 is schematic drawing of the connections used for the subtraction divider.

Assuming a requirement of tap-to-tap measurements between T_1 and T_2 at the high-voltage end of the winding W, the applied surges are entering at S. These may be single-surge applications from high-voltage surge generator or a timed train of surges from the oscillograph electric-transient analyzer.

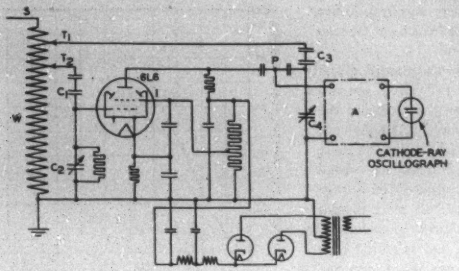

Figure 8. Subtractive voltage-divider circuit for tap-to-tap records

Capacitor combinations C_1, C_2, and C_3, C_4 are similar voltage dividers which must be sufficiently low in capacitance to give no appreciable wave distortion at the intermediate tap point. This is an important and exacting requirement.

Unit I is an amplifying inverter and A an amplifier. At point P the voltage waves from the left and right divider superimpose and are of opposite voltage polarities. The oscillograph through amplifier A, therefore, records the voltage between P and ground which is equal to the instantaneous differences between the voltages at P from the left and right dividers.

Preliminary adjustment of this circuit is accomplished by connecting the tap point terminals T_1 and T_2 together at T_1 and adjusting C_3 and C_4 for no deflection on the oscillograph. This proves a correct balance of the two waves arriving at P. Moving the left capacitor lead to intermediate tap point T_2 now gives the required tap-to-tap voltage difference.

Particular precautions are necessary in setting up such a circuit to provide for accurate results. The capacitance divider should be permanently built in a very symmetrical arrangement to provide for a minimum of unbalanced voltage interference effects, and when in use should be so adjusted that the amplifiers are not carried beyond their saturation points. The inverter must be built to include a minimum of time lag between the incoming grid voltage from the capacitor C_1C_2 and the output plate voltage to point P. The amplifier at A must have a wide-range frequency response and a high input impedance. In balancing the whole arrangement it has been found possible to add sufficient lead length at T_1 to balance against some lag in I which cannot be eliminated otherwise.

Conclusions

Recent rapid progress in impulse testing has emphasized the importance of an understanding of the surge mechanism of the circuit under test and analyzer equipment has been developed which provides for direct demonstrations of this mechanism.

For the recording of test waves in impulse-voltage testing precision methods of timing have been made available which provide for improved accuracy of recording with the cathode-ray oscillograph, especially for wave-front testing.

The necessity of careful attention to surge-generator grounding conditions has been increasingly recognized and practices have developed wherein disturbing oscillations particularly in the measurement circuit are considerably relieved.

A circuit which permits the recording by cathode-ray oscillograph of voltage increments between tap points at high absolute voltage levels has been designed and tested.

The cathode-ray oscillograph is the best indicator of damage in impulse testing, because it provides for both simultaneous visual observation and permanent film records of test wave distortions and choppings.

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Discussion

Victor Siegfried (Worcester Polytechnic Institute, Worcester, Mass.): Messrs. Foust and Rohats are to be complimented on the thoroughness with which they have reported their progress in this rather specialized art of impulse testing. Their contribution will aid greatly in reducing the intangibles and increasing the real understanding of the behavior of surges in laboratory and field apparatus.

One question is raised by the authors which might bear even more consideration, namely, keeping the potentials of the deflection plates symmetrical with respect to ground. This is discussed in regard to the timing-axis plates for the transient analyzer, and has been provided for similarly in the circuit for the oscillograph, figure 2, where the ground potential lies midway between the time-axis deflection plates. However, would it not be equally important to maintain symmetrical potentials on the vertical (surge) deflection plates? Usual circuits with the resistance divider inherently ground one of these plates, in which case this ideal may not always be practicable. To be consistent, then, the calibration voltage must also be applied with the same plate grounded so that any nonuniformity in sensitivity will apply equally in both cases. Do the authors know of any way of obtaining a phantom ground for these deflection plates?

The practice recommended by the authors of bringing ground points of all parts of the surge generator and measuring circuits together is most heartily subscribed to. As we approach the faster wave fronts comparable with television frequencies, it may be helpful to refer to the parallel experiences of television engineers, whose similar difficulties with stray effects are being remedied by the same procedure.

P. H. McAuley (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): In reviewing the section on "Surge Generation Circuits", it is interesting to note the different practices that exist in different laboratories. Concerning grounding and shielding, laboratory techniques are very similar. On the other hand, we have seldom used a resistor at the generator end of the divider cable as the authors advocate. It has never appeared necessary, even for short-time measurements, and constitutes another item requiring occasional checking for maintenance of accuracy in results. Similarly, we have avoided damping resistors in the oscillograph deflecting plate leads, always trying to control spurious oscillations at their source in the circuit, rather than damping them out in the measuring circuit. Of course, with capacity dividers it has been found necessary to use damping resistors.

The surge-generator circuit of figure 3 of the paper shows the series resistance R_1, lumped at the generator terminal and a capacitor C_3 connected in parallel with the test piece. With R_1 and C_3 variable, control of the wave front is obtained. Our practice differs in that the resistance R_1 is distributed throughout the main capacitor bank and use is thus made of the natural capacity to space of all parts at high voltage to control the wave front. Particularly for tests with the standard 1.5x40-microsecond wave this method has several decided advantages:

1. Better use is made of the generator voltage rating whereas the addition of terminal capacity definitely derates the generator in voltage. Slightly less series resistance can be used in the latter case but the net effect is appreciable loss in maximum output voltage when a shunt capacitor is used.

2. Making use of the stray capacity of the generator by distributing the series resistance is more logical than adding an expensive capacitor, which is poor economics in most cases.

3. Because of the unavoidable stray capacity, the suppression of oscillations is much more difficult when R_1 is lumped at the terminal. Mathematically and practically it can be shown that R_1 is more effective when distributed along the capacitor bank. This is where oscillations should be controlled rather than in the measuring circuit.

For these reasons, even when a shunt capacitor may be desirable for wave-front control over wide ranges, it is better to have the series resistance distributed.

One point not stressed by the authors is the effect of lead lengths in the discharge and measuring circuits. In 1938 some tests were made at the Trafford laboratory with a 10-inch rod gap in parallel with a 150-centimeter sphere gap on steep-front voltage waves. With the circuits through each gap about 40 feet in length, both gaps flashed on each impulse with the sphere spacing varied between 5.55 and 16.2 inches. At shorter or longer spacings one of the gaps only flashed. This is almost a three-to-one ratio in the sphere gap spacing. When an additional 70 feet was added to the lead to the 10-inch rod gap, 50–50 sparkover between the gaps was obtained for 22.3 inches spacing on the sphere gap and was quite critical. These results illustrate the importance of leads in the testing circuits and their possible effect on measurements. The performance of a rod gap judged by its characteristics as determined at its terminals may be greatly influenced by the addition of a few feet of lead. Conversely, in measuring the characteristics of apparatus on steep-front waves, precautions must be taken to obtain a true picture of the performance.

Morris Newman (University of Minnesota, Minneapolis): Basing our opinion on our own experience we feel in complete accord with the developments in impulse-voltage testing given in the paper by C. M. Foust and N. Rohats. We should like to add the suggestion that the cathode-ray oscillographs with which most laboratories are equipped at present could be simply converted to exterior photography of the

Figure 1. Arrester on 1,000 kv per microsecond

fluorescent screen trace by the use of a miniature 35-millimeter film camera and the recently developed high-speed films. We have taken, for example, using a redesigned cold-cathode-ray high-voltage oscillograph, about 70 oscillograms on a small standard film roll, in test work, just as fast as the surge generator could be recharged, developed the film ready for inspection in five minutes and, after a half-hour of fixing, washing, and quick drying, projected it onto a large eight-foot by eight-foot screen for inspection of minute details. The oscillograph remained ready for instant use in rechecking or for further tests since it was not necessary to disturb the vacuum. We therefore very heartily concur with Mr Foust in recommending the advantages of exterior photography.

Also, while agreeing with the desirability of using symmetrical voltages on the oscillograph sweep plates when possible, we feel that such a measure minimizes the effect of nonuniform fringing field beyond the deflection plates but does not remove the cause completely, although it may do so for most practical purposes. We should like to suggest from experience that linear and constant deflections in both the timing and phenomenon voltage sweeps are obtainable by shaping the field beyond the plates, with a system of shielding surfaces and properly shaped passages, so that the beam electrons emerge through the same field conditions independently of their position in a perpendicular direction to the direction of the deflecting field. With care in controlling the fringing field we have found it possible not only to obtain constant deflection over the full sweep with voltage to just one of the plates, which is generally far more convenient, but we could then move the beam electrostatically instead of electromagnetically into any desired location by application of an easily controllable d-c biasing voltage to the opposite deflection plate.

Finally, we too have found an initiating "impulse transformer", which in our work was a Tesla coil, a useful economical substitute for a separate initiating impulse generator for synchronizing longer-time phenomena; and parallel to our experience we note that Messrs. Foust and Rohats have been quite aware, and have pointed out, that such a scheme would not be suitable for fast fractional-microsecond timing precision. But we do differ on the advisability of obtaining the desired delays for getting the oscillograph into operation through the insertion of the delaying resistance B in figure 2 of the paper under discussion. Such a delay in the impulse-generator switching process will, in fast front-of-wave work show up as a jog in the lower part of the voltage-wave-rise trace As a matter of fact such delays in the first few stages of the impulse generator often occur even without insertion of resistance and we find it indeed desirable to eliminate these delays entirely by simultaneous initiation of the first three or four of the intermediate gaps rather than of only one, in order to obtain a more smooth rate of voltage rise output of the generator (figure 1 of this discussion). Therefore we should recommend a separate initiating surge-generator circuit covering the entire range of synchronization times in preference to the dual range "impulse transformer" and "impulse generator initiation delay" combination scheme if very fast front-of-wave work, such as in the testing of low-voltage equipment, is involved.

The last suggestions of this discussion are offered not in criticism, but as specialized refinements which some laboratories may possibly find will lead to further development of impulse voltage research technique. We feel that C. M. Foust and N. Rohats have done an admirable job of presenting impulse-testing developments which should go far toward eliminating discrepancies still unfortunately to be found in surge testing.

W. F. Skeats (General Electric Company Philadelphia, Pa.): In a recently installed 3,000,000-volt impulse generator, careful attention was given to many of the points mentioned in the paper by Messrs. Foust and Rohats. The general form of this generator is quite similar to that made familiar by the New York World's Fair generator, except that for the lower voltage only 30 capacitors are used and these are arranged in one unit of four columns,

Figure 2. 3,000,000-volt impulse generator

as shown by figure 2 of this discussion. A plan of the layout is shown in figure 3.

Of greatest interest at the moment are the precautions taken in connection with the ground circuit for two purposes:

1. To eliminate spurious oscillations in the cathode-ray-oscillograph record, and

2. To obviate local potential differences in the ground circuit which might be dangerous to personnel or equipment.

The general principles followed in this connection were:

1. Concentration of all grounds at a single point and connection of this point by a short heavy conductor to a good earth ground.

2. Avoidance of all parallel ground connections except as required in laying more than one conduit between two points; in such cases all conduits were kept within a few inches of each other throughout their length.

3. Enclosure of all control-power wiring in metal conduit which served as the ground connection between the various parts of the apparatus.

4. Introduction of control-power wiring to the system only at the main ground point.

5. Connections on three sides from the main ground point to the building steel.

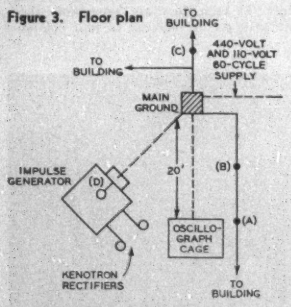
6. Enclosure of the control desk and cathode-ray oscillograph in a metal cage large enough to accommodate the operator and one or two observers. This cage used wide mesh screen on three sides and metal sheet on top, bottom, and the fourth side, all solidly connected electrically and grounded by conduit to the main ground. This is in addition to the sheet-metal housing of the oscillograph itself.

7. The deflection lead is a well-insulated concentric cable passing from the main ground to the control cage in a copper pipe from which the cable sheath is insulated except for the connection at the ground end. The control cage is connected to the

copper pipe but the oscillograph housing proper is connected to the cable sheath.

Enclosure of the control wiring in metal conduit gives it good protection from any harmful induced voltage. Electromagnetic induction may cause a potential gradient along the conductor, but except for minute differences due to displacement of the conductor from the center of the conduit or to local irregularities in the magnetic field, the same potential gradient is induced along the conduit. Thus unless there is a conducting path along which current may flow to relieve the gradient in one or the other, there is no resulting potential difference between them. Such a path has been carefully guarded against. Electrostatic induction may cause a local disturbance of potential, but again conduit and inside conductor suffer the same charge, and by skin effect the current which flows on account of this potential disturbance flows entirely in the conduit. The inductive potential gradient due to this current flow is again equal in both conduit and conductor, leaving only the resistance drop as a source of potential difference between the two. In the oscillograph deflection lead even this resistance drop is eliminated, by the copper pipe outside the sheath.

Figure 3. Floor plan



Solid lines—Ground conductors on test floor
Dashed lines—Ground conductors below test floor

From main ground, 1 / -inch copper pipe passes through floor, basement, and basement floor to a multiple driven ground

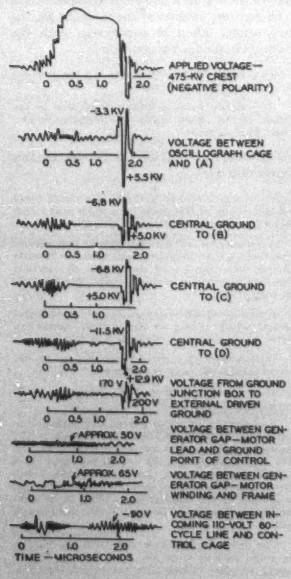


Figure 4. Voltage measurements

Thus the potential difference between wiring and the ground system may vary very little throughout the system. In order to keep this potential difference low, owever, one further precaution is necessary: the wiring must enter the ground system at a point where it is subject to but little variation from true earth potential. For that reason, all wiring enters this system at the "central ground point".

In order to check the arrangement, a steep-front wave reaching a crest of 475 kv in about half a microsecond and chopped at about 15 microseconds by a 20-inch rod gap was applied and various voltage measurements made throughout the circuit. The results are shown in figure 4 of this discussion.

These results may be summarized as follows:

1. The most severe voltages occurred at the time of chopping of the wave.

2. Voltages from one to three per cent of the crest value of the applied impulse were measured over comparatively short runs of heavy conductors in the ground system. Most spectacular of these is the voltage of 5.5 kv measured between the control cage and a ground strap running less than a foot away from it and connected over a loop of about 50 feet of heavy conductor. This voltage was checked approximately by means of a sphere gap and found to be correct.

3. The potential difference between the "central ground point" and a driven ground outside the building was limited to about 300 volts—0.06 per cent of the applied wave.

4. The potential difference between frame and winding of the motor for controlling the generator gap spacing, which is located at the base of the impulse generator; the potential difference between leads to this motor and the control cage ground; and the potential difference between the incoming 60-cycle leads and the control cage ground—all were less than 100 volts—0.02 per cent of the applied wave.

Thus voltages within the system are controlled to a satisfactory extent. The relatively high voltage measured on the ground straps connecting with the building steel together with the much lower voltage between the "central ground" and outside earth seems to indicate that the major stray voltages are associated with charges induced on the building steel.

C. M. Foust and N. Rohats: Mr. Siegfried discussed the use of balanced voltages in sweep circuits which are necessary to give uniform voltage sensitivity throughout the time axis. With balanced sweeps, d-c calibration lines are parallel, with unbalanced sweeps d-c lines converge. Having a balanced sweep, a balanced deflection voltage would be desirable only from the standpoint of improving the focus. The authors have thought of two ways to obtain symmetrical deflection potentials but have not tried them as both would detract somewhat from accuracy. One way was to place the main ground point at the midpoint of the portion of the resistance divider connected across the deflection plates. In this case the current flowing in the part of the divider between ground and the surge generator would be different from that between ground and the divider because of the addition of charging currents returning from the surrounding building structure. The other way was to leave the main ground at the end of the deflection resistance and connect the oscillograph ground to its midpoint. In this case the oscillograph would be raised to one-half of the deflection voltage, thereby drawing some charging current from the divider. It is possible, however, that this would be negligible especially with a low-resistance divider.

The surge-testing equipment at Philadelphia described by W. F. Skeats incorporates ground-connection arrangements designed with great attention to detail, in view of giving a minimum of circuit oscillations and measurement circuit disturbances. The authors wish to thank Mr. Skeats for his contribution to this discussion.

Morris Newman's comments on outside photography bring to attention a number of interesting considerations. Since the fast cameras required have a very shallow depth of focus the screen would have to be essentially parallel to the film. In this position it could hardly be perpendicular to the central position of the cathode beam and this would mean some correction of the record. Another way would be to have a mirror somewhere between the camera and the screen.

The authors are heartily in agreement with the suggestion of shielded deflection plates, but a tube with such plates is not at present commercially available.

In regard to the use of a delay resistance within the surge generator for wave-front work, the authors' experiences have been that serious oscillations are not obtained. Another simple circuit arrangement has been worked out by J. W. Beatty of Philadelphia. This involves using the initiating impulse transformer the same as for slower work but having several microseconds delay in the oscillograph sweep circuit to counterbalance the delay in the tripping of the surge generator. This delay is obtained by coupling the rod sphere of the sweep trip gap to the initiating circuit through resistance instead of capacitance. The delay may be varied by adjusting the gap setting. This scheme in addition to doing all that the previous method could do has the added advantage of being able to retard the sweep so much that instead of spreading out the front of a wave on the screen some later section of the wave, such as the flashover part, may be brought out in detail. To minimize delays in the spark-over of the first several gaps of a surge generator, they should be arranged in line so that the ultraviolet radiation from the first gap will fall upon and ionize all of the remaining gaps.

The authors appreciate the comments of P. H. McAuley pertaining to the measurement and discharge circuits. The impor-

tance of surge impedance at both ends of a resistance-divider cable varies directly as the length of the cable. With cables of about 50 feet or less only the oscillograph end need have surge impedance across it. With cables of 20 feet or less, the value of the resistance across the cable becomes of no importance. The 200 ohms damping resistance shown in the deflection plate leads are too small to damp any oscillations of such frequency as may arise in the generator circuit, but are enough to suppress such high-frequency local oscillations as may arise in the deflection plate circuit.

With reference to the location of the series resistance in the surge-generator discharge circuit, the authors have found in practice that about 200 ohms distributed within the generator and the remainder R_1 placed externally give the best results. While the economic question of surge-generator efficiency is important, it is secondary to that of good waves and consistent results. On this basis the amount of resistance R required for control of oscillations generated within the capacitor bank was determined experimentally and this resistance was distributed in 20 resistors, one on each side of the ten interstage gaps in use. From this point on, the important considerations are the generation of the required wave shape, its maintenance at all voltage levels, and consistency of test results. Here the authors' experience has been that the value of capacitance across the test piece is quite significant especially for short-time tests and that extra load capacitance C_2 ranging up to ten per cent of the generator capacitance for most work and on special occasions up to 25 per cent is of decided value and justifiable despite some loss in generator efficiency. With values of generator capacitance C_1 and load capacitance C_2 in mind, the oscillograph electric-transient analyzer is used to determine the series resistance $(R+R_1)$ and parallel resistance R_2 for the wave required. With R_1 outside the generator bank, it can be conveniently changed for any wave required.

The efficiency of a generator is dependent upon wave-shape requirements. If the load capacitance C_2 consists only of generator stray capacitance, the series resistance $(R+R_1)$ must be high and efficiency suffers just as much as if C_2 were high and $(R+R_1)$ were low. With a high C_2 made up of extra load capacitance in parallel with the test sample, the wave shape will be more rigidly maintained as both high capacitance and low resistance make possible higher currents into the test piece for corona and flashover streamers. In view of the high energy rates involved in disruptive discharges, it is reasonable to expect the more rigid circuit to give values nearer that required and certainly more satisfactory for comparison purposes.

In considering comparative results it is important to bear in mind that two circumstances are involved, one having to do with comparative results on different apparatus and involving the basic question of insulation co-ordination and the other having to do with comparative results between laboratories on the same apparatus and involving testing equipment and measurements. Results are comparable only in so far as applied waves are similar at all voltage levels.

Load-Rating Theory for Multichannel Amplifiers

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Synopsis: The amplifiers of multichannel telephone systems must be so designed with regard to output capacity that interchannel interference caused by amplifier overloading will not be serious. Probability theory is applied to this problem to determine the maximum single-frequency output power which a multichannel amplifier should be designed to transmit as a function of N, the number of channels in the system. The theory is developed to include the effects of statistical variations in the number of simultaneous talkers, in the talking volumes, and in the instantaneous voltages from speech at constant volume.

IN a perfect multichannel carrier telephone system, each channel would be entirely free from interference produced by the energy present in the other channels. Since all the channels are amplified by the same repeaters, which as a practical matter cannot have perfectly linear characteristics, this is an ideal that may be approached but not completely realized. The interchannel interference must be kept down to a value which will be satisfactory for the grade of transmission concerned, further reduction being uneconomic. To do this the repeaters must meet definite load-capacity requirements and modulation (nonlinearity) requirements. The load-capacity requirement is most conveniently specified in terms of the maximum single-frequency sine-wave power which a multichannel amplifier must transmit without appreciable overloading. The modulation requirement pertains to the performance of the amplifier for impressed loads equal to or smaller than the load capacity, and specifies the allowable power in the modulation products resulting from such loads. Because of the numerous factors which affect these requirements, their determination is a rather complicated matter and the present discussion will be restricted solely to a determination of the load-capacity requirement. The object is to determine this quantity as a function of N, the number of channels in the system.

The criteria ordinarily used for determining the load capacity of single-channel amplifiers are of little use here because of two fundamental differences between single-channel and multichannel systems. In the first place, the modulation produced in a single-channel amplifier depends only upon the input to that channel and occurs only when the channel is energized. In addition, the most important frequencies resulting from modulation fall directly back upon frequencies already impressed and the net effect appears as a distortion of the original input, rather than as noise. The situation is entirely different in a multichannel system. In this case, the modulation products falling into one particular channel are in the main unrelated either to the impressed frequencies or to the volume of impressed speech in that channel. Thus it is no longer possible to think of the interference as distortion; the effect must rather be considered as that of a particular kind of noise whose level depends upon the load on the other channels of the system. For a given grade of service, the ratio of signal to noise must be much larger than the ratio of signal to modulation products resulting in distortion; thus it is to be expected that the nonlinearity requirements will be more stringent for multichannel operation than for single-channel operation.

The second fundamental difference between single-channel and multichannel systems arises from the character of the load which each system must be designed to handle. A single-channel amplifier must be capable of handling one channel at the maximum volume normally expected. Inasmuch as the amplifier will be loaded only about one-fourth of the time, even in the busiest hour, and as the averaged impressed volume will be some 15 decibels below the maximum that must

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Many members of the Bell Telephone Laboratories, in addition to those mentioned in the text, have contributed to various phases of this work. The authors take this opportunity to acknowledge their indebtedness to these colleagues, and in particular to Doctor G. R. Stibitz, who first developed the theoretical approach here used.

be provided for, the ratio of maximum to average load of such an amplifier is inherently very high. In a multichannel system, however, the several channels will very rarely be heavily loaded simultaneously. There is thus a favorable diversity factor, increasing with the number of channels, and multichannel amplifiers may accordingly be worked successfully at lower ratios of maximum to average load.

Occasionally, of course, there will be short periods of excessive loading during which the interchannel interference in multichannel systems will rise above the value normally permitted. This sort of thing often occurs when it is desired to make economical use of facilities of any kind in common. In machine-switching systems, for example, it is common practice to associate a large number of lines with a smaller number of switches and trunks. The number of switches and trunks provided is sufficient to ensure a satisfactory service, with a very small probability of requiring more facilities than are available. The multichannel amplifier problem presents a situation identical in principle, though the methods of solution are necessarily very different. The application of probability theory is evidently indicated as the method of attack.

Those characteristics of multichannel amplifiers which are important to the problem will be described first. Then a description will be given of the variables which must be taken into account in computing load capacity. Finally, the combined effects of these variables will be determined on a statistical basis to establish the required load capacity as a function of the number of channels in the system.

Characteristics of the Multichannel Amplifier

At the present time, multichannel systems of primary interest employ single-side-band transmission; the carrier frequencies are largely suppressed and different amplifiers are used for the two directions of transmission. For such systems negative-feedback amplifiers have outstanding advantages, particularly with respect to stability of gain and reduction of modulation effects, and are thus being used almost exclusively in present-day multichannel systems. The following discussion is related particularly to such systems, although many of the calculations are also applicable to less common types.

At light loads the principal modulation products in a negative-feedback amplifier increase approximately as the square or the cube of the fundamental output power. Beyond a certain critical point, however, the modulation increases very rapidly and the total output of the amplifier soon becomes practically worthless for communication purposes. This critical point will be called the "overload" point. For most tube circuits it is either the point at which grid current begins to flow, or that at which plate-current cut-off occurs. This point obviously defines the instantaneous load capacity.

Below the overload point the higher-order modulation products are negligible in comparison with second- and third-order products, and the interference may be regarded as due to the latter sources alone. Beyond the overload point, however, the higher-order products become important very rapidly and the resultant disturbances appear in most, if not all, of the channels. With given tubes, the interference below the overload point may be altered by changing the amount of feedback. The interference above the overload point, however, may be little changed in this way because of the rapid loss of feedback as the amplifier overloads. Accordingly, in designing an amplifier, the necessary load capacity may be determined solely by insuring that the output will rarely rise above the overload point, afterward adjusting the amount of feedback so that the interference below the overload point will be tolerable. There are thus two problems which may be handled separately, at least for negative-feedback amplifiers, it being understood that the results are combined in the final design. As previously stated, only the load-capacity problem will be considered in detail here but many of the methods used have been applied successfully to the interchannel-modulation problem.

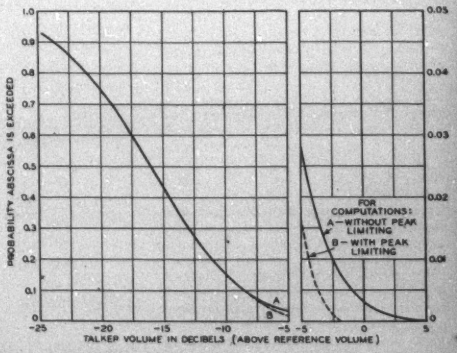

Figure 1. Talker volume distribution

The Load on a Single Channel

The total load applied to a multichannel amplifier varies rapidly between widely separated limits. A complete knowledge of the variations in the load applied to a single channel is necessary first; these variations arise from several recognizable causes which may be discussed separately.

Number of Active Channels

First of all, a single channel at a given instant may or may not be carrying speech; if not, it contributes nothing to the multichannel load. A channel will be called "active" whenever continuous speech is being introduced into it; that is, a channel is active during the time it is actually carrying speech power, and also during the short pauses that occur between words and syllables of ordinary connected speech. A channel is said to be "busy" when it is not available to the operator for completing a new call. Busy time is by no means all active time, for a busy channel is inactive during much of the time the connection is being completed, during pauses in the conversation, and finally during the time the other party is talking. The fraction of time during the busiest hour that a channel may be busy depends on the size of the group of circuits of which it is a member and on the methods of traffic operation. Measurements on circuits in large groups, made by M. S. Burgess, indicate that the largest fraction of the busiest hour that a channel may be active is about one-fourth. For channels in small circuit groups, this figure may become considerably smaller but it is unlikely that

any probable increase in group size or improvement in operating practices will increase it appreciably. This figure, which will be represented by τ, may accordingly be taken as a conservative estimate of the limiting probability that a channel will be active in the busiest hour.

The number of channels that are active at a given instant in an N-channel system may be anything from zero to N. Inasmuch as the channels are independent, it is possible to write down at once the probability that exactly n of them are simultaneously active. This probability is

$$p(n) = \frac{N!}{n!(N-n)!}\tau^n(1-\tau)^{N-n} \qquad (1)$$

Talking Volumes

A second source of variation in the load on a given channel is that the impressed volume may have any value within rather wide limits when a channel is active. By "volume" is meant the reading of a volume indicator of a standard type. Its importance in the present problem arises from the fact that the volume is an approximate measure of the average speech power being introduced into the channel. Although some other instrument might give a better measurement of the latter quantity, only the volume indicator has been used sufficiently widely in the plant to give data on the distribution of average speech power per call under commercial conditions. The average speech power is dependent on the type of instruments, the character of the speech, and the time interval over which the average is determined. From an analysis of phonograph records of continuous speech it is found that the average speech power of a reference volume talker may be taken as 1.66 milliwatts, and the relationship between volume* and average power may be expressed by the following equation:

$$\text{Volume (decibels)} = 10\log_{10}\frac{\text{average speech power in milliwatts}}{1.66} \qquad (2)$$

This equation is based on the long-average speech power. It will be understood that for purposes other than load-rating computations, a different relation might be found more suitable.

The use of equation 2 to relate volume to average speech power is applicable to speech in a single channel. It is convenient to refer to a quantity related in the same way to the total average power contributed by a number of channels as the "equivalent volume".

The single-channel volumes on commercial circuits are conveniently measured at the transmitting toll test board, which will be taken as a point of "zero transmission level". Henceforth it is assumed that there is no gain or loss between this point and the output of the amplifier, so that the latter is also a point of zero transmission level. While this will seldom be the case in an actual system, the necessary change in the load capacity is easily computed. The volumes at this point are found to be distributed approximately according to the "normal" law; that is, the probability that the volume will be between V and $V+dV$ is given by

$$p(V)dV = \frac{1}{\sqrt{2\pi}\sigma}\epsilon^{-\frac{(V-V_0)^2}{2\sigma^2}}dV \qquad (3)$$

For calls on typical toll circuits, the best present values for the parameters are $V_0 = -16.0$ decibels and $\sigma = 5.8$ decibels. These parameters depend, of course, upon the character of the local plant and upon the habits of telephone users, and changes in either will affect their values. Curve A of figure 1 shows this distribution of talker volumes at a point of zero transmission level. Curve B of figure 1 is the talker-volume distribution used for load-rating computations when a particular amount of peak amplitude limiting occurs in the terminal equipment. This will be discussed later. Although the mean volume is V_0, the volume corresponding to the mean power of the distribution (3) is equal to $V_0+0.115\sigma^2$, as may be seen by converting the volume scale of the distribution to power ratios, averaging, and reconverting the average to volume in decibels. For the values of the parameters given above, $V_0+0.115\sigma^2 = -12.1$ decibels.

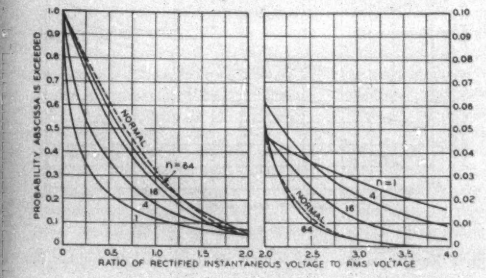

Figure 2. Instantaneous voltage distributions for n talkers

Instantaneous Voltage Distribution

Finally, the voltage in an active channel fluctuates widely even at constant volume. Not only the differences between successive syllables and the differences between vowel sounds and consonants, but also the fine structure of single sounds, are important in this connection. The total voltage impressed on the amplifier is the quantity which determines whether or not it will overload, and the phases as well as the amplitudes of the frequency components in the several channels must be considered in determining this. It is most convenient for analysis to work directly with instantaneous voltages of speech, the frequency of occurrence of the magnitudes being expressed in the form of a distribution function.

This distribution function has been measured by Doctor H. K. Dunn, using apparatus which measures 4 samples per second of the instantaneous voltage out of a commercial subset and typical loop. By operating the apparatus until about 1,000 successive samples have been measured, usable distribution curves of instantaneous voltage are obtained; this is readily checked by making repeated runs comprising the same number of samples on speech recorded on high-quality phonograph records. It is, of course, known that commercial transmitters have considerable asymmetry as regards positive and negative voltages but the poling referred to the toll board is expected to be random. As the measurements were considerably simplified by doing so, it appeared desirable to average out this asymmetry by arranging a linear rectifier ahead of the sampling apparatus to obtain equal samples of positive and negative voltages.

Such measurements have been made for a number of different talkers, different

* Subsequent to the preparation of this paper, a new volume indicator was standardized for use in the Bell System. With the new volume indicator, volume is expressed in *vu*, +8*vu* being approximately equal to reference volume (0 decibels) as used herein.

commercial subsets, and different volumes, with the speech input held at substantially constant volume in each test. The various subsets now in commercial use all give essentially the same distribution curve. The resulting distributions, if they are considered as functions of the ratio of instantaneous to rms voltage, are also nearly independent of the speech volume at the subset. Specifically, the only important effect of volume is that which may be ascribed to amplitude limiting in the transmitter; that is, to the fact that the transmitter itself has a limited load capacity. However, this effect does not appear until the volume is ten decibels or more above the mean of the volume distribution curve, and is only of importance for talkers at still higher volumes. For all lower volume talkers, the instantaneous voltage distribution may be considered as the same for all volumes when expressed as a ratio of instantaneous to rms voltage. The cumulative distribution curve of the quantity E/U, where E is the rectified instantaneous voltage and U the rms voltage, is shown by the curve $n=1$ of figure 2.

Voltage Limiting

While this curve of figure 2 is accurate for the bulk of the talkers, it changes for the high-volume talkers who overload the subset transmitters. It is also the custom to provide a certain amount of amplitude limiting in each channel by suitable circuit design of the channel terminal equipment. This limiting alters the shape of the instantaneous voltage distribution curve for a range of voltages below the maximum, the extent of the modification depending on the talker volume and the characteristics of the limiting device. Its effect on the load capacity will be considered later.

Multichannel Instantaneous Voltage Distributions

The number of variables with which it is necessary to deal makes the general load-capacity problem rather a complicated one. The analysis will be easier to follow if the effects of the different variables are taken up one at a time, thus building up a complete theory in successive steps. To do this, it is advantageous to start with a case so simplified that it rarely, if ever, occurs in ordinary practice; that is, that in which the volumes in all the channels are regulated to a common constant value, and in which the number of *active* channels is also kept constant. For this condition, it is necessary to consider only the effects of the distribution of instantaneous voltages in each channel. This distribution curve is the same for all of the channels, since all are at the same volume, but the voltage in any channel at a particular instant is entirely independent of the condition of the other channels.

Overload Expectation

The total voltage impressed on the amplifier by a number of channels at a given instant is the sum of the instantaneous voltages in the separate channels. Since disturbances will be produced in many of the channels when the applied voltage goes beyond the overload point, it will be useful to know the fraction of the time that this may be expected to occur; this fraction will be called the overload expectation and denoted by ϵ. It is important to notice that this quantity ϵ is not necessarily the fraction of the time during which the performance of the amplifier will be unsatisfactory. This might perhaps be the case for a device having an instantaneous cutoff characteristic, but for an ordinary amplifier the time constants (among other things) affect the results of overloading. The interpretation of the overload expectation will be discussed further later; consideration must be given first to how it is obtained.

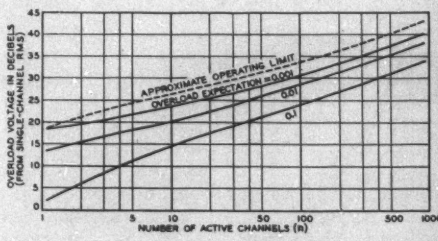

Figure 3. Overload voltage for n active channels

The n-Channel Voltage Distribution

The load in each channel is applied at voice frequency to the input side of a modulator, the voice-frequency instantaneous voltage distribution being as shown by the curve $n=1$ of figure 2. The overloading of the amplifier is determined, however, by the distribution of the sum of n such voltages after each has been shifted by the modulator to the appropriate carrier frequency, one sideband being suppressed. It may be shown that if the phases of the various components of the voice-frequency input were random, the distribution of instantaneous voltage at side-band frequency would be identical with that measured at voice frequency. It is known, however, that the phases at voice frequency are not entirely random, and there may thus be differences between the two distributions. The results of a number of tests bearing upon this point indicate that any error resulting from the use of the distribution measured at voice frequency will be small for systems of few channels, and will rapidly disappear as the number of channels is increased.

Theoretically, the resultant n-channel voltage distribution can be derived from the single-channel distribution by straightforward analytical methods; in the present case, however, expression of the result in useful form is very difficult because of the form of the single-channel curve. This difficulty might be resolved by using graphical or numerical methods, as applied later to the volume-distribution curves; fortunately, the fact that the voice-frequency voltage distributions may be used throughout permitted the resultant n-channel distributions to be obtained much more easily. Since the addition of voltages from the several carrier channels does not depend materially upon the frequencies at which the channels appear in the system, the addition of n channels at voice frequency will give the desired n-channel distribution directly. M. E. Campbell effected this addition by the use of phonograph records, the n-channel distributions being determined by means of the instantaneous-voltage sampling apparatus previously mentioned.

As material for this process, 16 high-quality phonograph records were made of the outputs of commercial subsets through representative subscriber loops. Both male and female voices were used. The speech was furnished by reading magazine stories containing considerable conversational material, due precautions being taken that the volume on each

record was substantially constant throughout. A calibrating tone was cut on each record to enable it to be played at any desired volume and most of the volumes recorded were well below the point at which the transmitter began to act as a voltage limiter.

These individual records were then combined in groups of four, with all records adjusted to the same volume by means of the calibrating tones, and re-recorded. Several such 4-voice records were made; by combining them again in the same way, 16-voice records and finally 64-voice records were obtained. The instantaneous voltage distributions were measured before and after each re-recording to insure that the recording process introduced no errors. A few minor discrepancies were found, but all were small enough to be disregarded. Each single-voice record appeared several times in a 64-voice record, but since the phases of its different appearances were random, this had no appreciable effect on the resultant voltage distribution. This was verified by comparing the voltage distributions of the various possible 16-voice combinations. By this process n-channel voltage distributions were obtained for $n=1$, 4, 16, and 64.

These distributions, together with a normal curve, are shown in figure 2 in cumulative form. To show the curves conveniently to the same scale, it has been necessary to plot for each case not the distribution of E, the rectified instantaneous voltage, but that of E/U, where U is the rms voltage. The rms voltage, it will be remembered, is directly related to the equivalent volume by equation 2. The figure shows clearly the gradual transition from the single-channel distribution to the normal one for large n, and also indicates that for 64 active channels the curve is normal within the precision of the measuring apparatus. Hence, the normal distribution may justifiably be used for any value of $n>64$.

Further significance is accorded the above data by plotting the ratio of the voltage exceeded a fraction ϵ of the time to the single-channel rms voltage, as a function of the number n of active channels, for several fixed values of ϵ. From the data given, points on such curves can be obtained for $n=1$, 4, 16, 64; furthermore, the fact that the distribution for $n>64$ is normal permits drawing the asymptote for large values of n. The points read from figure 2 and replotted in this way give the full lines shown in figure 3.

In order to make practical use of these curves, it is necessary to know what value of ϵ corresponds to satisfactory performance of the amplifier. Experiments have been conducted on a number of different multichannel amplifiers, each loaded by various numbers of active channels all at the same volume. It has been found that for low enough values of ϵ, no audible disturbance is produced but that as ϵ is increased by increasing the load on the amplifier, the disturbance falling into a channel not energized increases rapidly to a large value. Two different amplifiers having the same computed load capacity may show noticeable differences in performance in this respect when subject to identical fixed loads of the type being considered, thus indicating the influence of circuit design on the value of ϵ. In general, however, the allowable values of ϵ measured for all of the amplifiers that have been tested lie in a relatively narrow band on either side of the curve for $\epsilon=0.001$. The broken curve of figure 3 represents the approximate upper limit of the observations, extrapolated parallel to the $\epsilon=0.001$ curve above $n=14$. It is possible that some amplifiers would overload even if operated in accordance with this curve, but for the great majority of amplifiers of types thus far tested the operation would be satisfactory, with perhaps a small margin.

Multichannel Peak Factor

It is useful at this point to introduce the concept of "multichannel peak factor," which is defined as the limiting ratio of the overload voltage to the rms voltage for a given number of active channels at constant volume. The ratio of the overload voltage for n active channels to the rms voltage of one active channel is given directly by the broken curve of figure 3, and the rms voltage for n channels is simply $\sqrt{n}$ times that for one channel. A simple computation then gives the multichannel peak factor. This is plotted in figure 4 as a function of the number of active channels n. The reduction in multichannel peak factor as the number of active channels increases reflects the transition from the single-channel distribution curve to the normal curve, as depicted in figure 2.

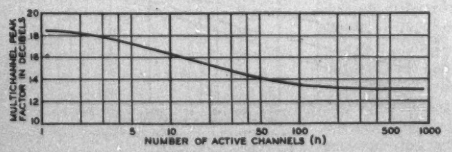

Figure 4. Multichannel peak factor for n active channels

The Distribution of Equivalent Volume

The multichannel peak factor deals only with the effects of changes in the instantaneous voltages of the channels, all other variables being fixed. It is next necessary to extend the treatment to include the effects of the other load variations that occur in practice—those in number of active channels and in channel volumes. It is important, first of all, to notice that the instantaneous-voltage variations occur very rapidly, while changes in the other two quantities are, in comparison, very slow. In the experiments described above, the loads were so fixed that the equivalent volumes could be changed only by changing the operating transmission level of the amplifier; in practical cases the amplifier transmission level is kept fixed, but the equivalent volume is constantly changing because of changes in number of active channels and in channel volumes.

The amplifier is thus loaded with a constantly changing equivalent volume but because of the great difference in the time-scales of the two classes of variations the load may be regarded as a succession of equivalent volumes, each constant for a small interval of time that nevertheless is long enough to include a representative sample of the resultant instantaneous voltage distribution. If the distribution function for equivalent volume is computed, and then corrected by the multichannel peak factor, the fraction of such intervals during which the amplifier will be unsatisfactory from the standpoint of overloading may be determined. For a particular amplifier, the operating transmission level must be so chosen that this fraction will be small enough to make any adverse effects on transmission unimportant. For systems of very many channels the proper value of this fraction is probably about one per cent. During the busiest hour, this corresponds to 36 seconds during which audible interference *may* occur and as this will be broken up into many very short intervals, the total effect should be

slight. For systems of very few channels, the equivalent volume may reach objectionably high values during these intervals and it might be necessary to make this fraction smaller than one per cent to secure good performance. For illustrative purposes, the one per cent figure will be used in what follows without implying that it may not need alteration in some cases. The methods used are applicable no matter what value is chosen for the fraction of time overloading is permitted.

Controlled Volumes

As the simplest case to which the above procedure may be applied, and one that may occasionally be of practical interest, consider a commercial system with all the channels controlled to the same volume. If there are N channels in the system, the probability that exactly n channels will be active at any given time is given by equation 1, with $\tau = 0.25$. By computing the value of $p(n)$ for all values of n, and taking the cumulative sum, the value of n which makes the sum 0.99 (or the next greater n) is readily determined. This determines the number n of active channels that is exceeded one per cent of the time. A plot of these values of n is given by the curve of figure 5, as a function of N, the number of channels in the system. For small values of N this curve has been drawn in a manner to smooth out the steps introduced because n must of necessity be an integer and when the value of n read from the curve is not an integer, the next higher integral value is to be used. It is of interest to compare this curve with the two straight lines of the figure. The lower straight line represents the asymptote for sufficiently large N and the upper straight line is for the condition where all channels are active simultaneously ($n = N$).

The average power for n channels is n times that of one channel, and the equivalent volume expressed in decibels is 10 $\log_{10} n$ above that in one channel. The equivalent volume may thus be computed as a function of n, and by means of figure 5, as a function of N. Curve A of figure 6 shows the values of equivalent volume so determined as a function of N, the number of channels in the system; it applies specifically to the case where the volume of each of the active channels is controlled so as to be 12.1 decibels below reference volume. The choice of this particular volume is purely arbitrary, but it corresponds to the average power of the single-talker volume distribution.

The equivalent volumes given by curve A of figure 6 are a measure of the average power of the N channels, as computed by means of equation 2. To determine the required instantaneous load capacity of the system, the average power must be corrected by the multichannel peak factor which is read directly from figure 4, using for the number of active channels the values read from figure 5.

For design purposes, it is more convenient to use the rms power of the single-frequency test tone whose peak value represents the instantaneous load capacity. As the ratio of the peak to rms power of a single-frequency tone is three decibels, this test power is obtained by subtracting three decibels from the instantaneous load capacity. This required test-tone capacity is plotted as a function of N in curve A of figure 7, which gives the output capacity required for an N-channel system with volume control as specified above.

Uncontrolled Volumes

For systems in which volume control is not used, the application of this procedure becomes more involved. To study this more general case, it is convenient first to interchange the conditions of the preceding section, letting the number of active channels be fixed at any value n and examining how the distribution curve of equivalent volume may be obtained for this fixed number of channels. The relation between volume and average speech power given in equation 2 may be rewritten for this case in the form

$$V_i = 10 \log_{10} \frac{W_i}{W_0} \text{ decibels}$$

where $W_0 = 1.66$ milliwatts, W_i is the average speech power in milliwatts, and V_i is the volume in decibels for any one of the active channels, all at a point of zero transmission level.

Likewise, the relation between equivalent volume and average speech power for n active channels is given by the expression

$$V = n\text{-channel equivalent volume} = 10 \log_{10} \frac{\sum_1^n W_i}{W_0} \text{ decibels}$$

Since the distribution of the channel volumes V_i is known and the volumes of the various channels are independent, the straightforward procedure to obtain the distribution of the n-channel equivalent volume V would involve the following steps: (1) the obtaining of the distribution function of W_i by a transformation of that of V_i; (2) the calculation of the distribution function for the quantity $Y(n) = \sum_1^n W_i$; (3) the transformation of

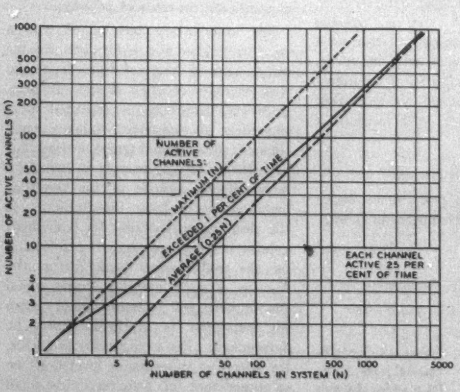
NUMBER OF ACTIVE CHANNELS (n)
NUMBER OF CHANNELS IN SYSTEM (N)
NUMBER OF ACTIVE CHANNELS
MAXIMUM (N)
EXCEEDED 1 PER CENT OF TIME
AVERAGE (0.25N)
EACH CHANNEL ACTIVE 25 PER CENT OF TIME

Figure 5 (left). Number of active channels as a function of the number of channels in the system

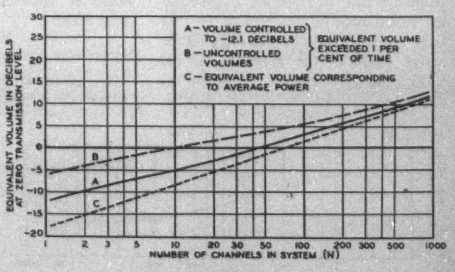
A – VOLUME CONTROLLED TO –12.1 DECIBELS
B – UNCONTROLLED VOLUMES
EQUIVALENT VOLUME EXCEEDED 1 PER CENT OF TIME
C – EQUIVALENT VOLUME CORRESPONDING TO AVERAGE POWER
EQUIVALENT VOLUME IN DECIBELS AT ZERO TRANSMISSION LEVEL
NUMBER OF CHANNELS IN SYSTEM (N)

Figure 6 (below). Equivalent volume for systems of N channels

the $Y(n)$ distribution to that of V by inverting the process used in step 1.

The difficulties in this process are all in the second step, where, having given $p_1(W)$, the distribution of average powers for a single channel, it is required to obtain $p_n(Y)$, the distribution for n active channels, with Y defined in terms of W by the relation given immediately above. The formal solution requires the evaluation of integrals of the following type:

$$p_n(Y) = \int_0^Y p_{n-k}(W)\, p_k(Y-W)\, dW$$

By successive calculation of such integrals for $n=2, 4, 8 \ldots$, taking k each time equal to $n/2$, the required distributions may be obtained for the necessary range of values of n.

As in the case of the instantaneous-voltage distributions, it has not proved feasible to perform the integrations analytically. It was necessary to resort to numerical evaluation of these integrals; by combining the transformations in steps 1 and 3 with the process of evaluating the integral, the process was somewhat shortened. In this way equivalent volume distributions have been obtained for $n=2, 4, 8, 16 \ldots$; needed points on the distribution curves for intermediate values of n are obtainable by interpolation.

The accuracy of such a process depends upon the number of division points used in the numerical integration and this as a practical matter must be kept fairly small. When the process must be repeated many times, the errors introduced at each step may accumulate and lead to inaccuracies for large n. It is thus desirable to have some control over the accuracy other than by repeating the calculation with a larger number of division points. This is provided by calculating the moments of $p_n(Y)$ from those of $p_1(W)$ without the use of numerical integration.

The moments S_k of $p_1(W)$ are defined by

$$S_k = \int_0^\infty W^k p_1(W)\, dW$$

and the moments $T_k^{(n)}$ of $p_n(Y)$ similarly. By the use of the semi-invariants of Thiele,* it may be shown that

$$T_1^{(n)} = nS_1$$

$$T_2^{(n)} = nS_2 + n(n-1)S_1^2, \text{ etc.}$$

By comparing the moments of the distributions obtained by numerical integration with those calculated in this way, and making occasional minor alterations in the curves to bring the first and second moments into agreement, assurance was obtained that all the distributions used are reasonably accurate, with no accumulation of error as n becomes large.

Examples of the cumulative distribution curves of equivalent volume for 1, 4, 16, and 64 active channels are given in figure 8. The decrease in standard deviation which occurs as n increases is of interest for it indicates how the fluctuations in load due to talker volume variations are reduced by combining a large number of channels in one system.

Having now n-channel equivalent volume curves for a range of values of n, the resultant equivalent volume curves may be calculated when the restriction to a fixed number n of active channels is removed. Let $p_n(V)$ denote the probability that, with n channels active, the equivalent volume lies between V and $V+dV$ and let $p(n)$ denote the probability that just n channels *will* be active. Then the total probability that the equivalent volume will be between V and $V+dV$ is given, for an N-channel system, by

$$p(V) = p(1)p_1(V) + p(2)p_2(V) + \ldots + p(N)p_N(V)$$

The $p_n(V)$ are given by equivalent volume curves such as those in figure 8 and the $p(n)$ by equation 1. Examples of curves thus computed are given in figure 9, which shows the equivalent volume distributions at a point of zero transmission level for 3, 12, and 240 channel systems. The equivalent volume that is exceeded one per cent of the time, read from such curves, is plotted as curve B of figure 6.

This curve gives, for any number of channels having uncontrolled volumes, the equivalent volume which will be exceeded just one per cent of the busy hour. To obtain the necessary load capacity, this must be corrected for the multichannel peak factor. In the controlled-volume case, for a given number N of channels in the system, there was no difficulty in deciding the value of n, the number of simultaneously active channels, for which the multichannel peak factor should be taken. Now, however, there is no unique relation between equivalent volume and the number n; in addition, the multichannel peak factors were measured with all n channels at the same volume, which represents a condition rarely holding on a system without volume control. It is apparent, however, that in the majority of cases in which the equivalent volume approaches values on curve B of figure 6, the number of simultaneously active channels will be greater than the average number $N\tau$ of active channels. Since the multichannel peak factor decreases as n increases, the peak factors for $n=N\tau$ active channels

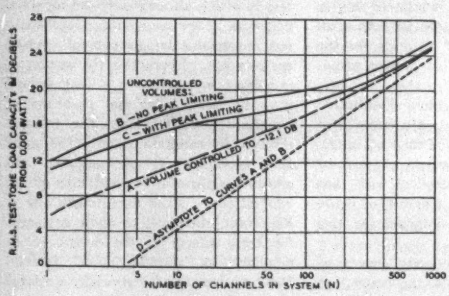

Figure 7. Load capacity for systems of N channels

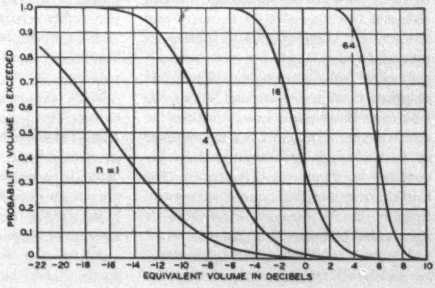

Figure 8. Equivalent volume distributions for n active channels

* T. N. Thiele, "The Theory of Observations," 1903; reprinted in *Annals of Mathematical Statistics*, volume 2, 1931. See especially sections 22, 29.

may be safely used. A more detailed analysis, feasible only for very small systems but avoiding the use of this approximation, shows that its effect is small and tends to give load capacities slightly higher than actually required, but the difference diminishes rapidly as the size of the system is increased.

For the uncontrolled volume condition, therefore, the multichannel peak factors are read from figure 5 for values of $n = N\tau$. They are added to the equivalent volumes obtained from curve B of figure 6, and reduced to single-frequency power as previously described for the volume-controlled case. Curve B of figure 7 is obtained in this manner and shows the load capacity required in an amplifier for an N-channel system in which the volumes of each channel are distributed in accordance with curve A of figure 1. The load capacity which is approached asymptotically as N increases indefinitely is represented by curve D of figure 7.

The load capacities given by figure 7 are valid only for systems for which the basic single-channel data apply. As these may not hold in specific cases, and may be subject to modification in the future, estimates of the effects of small changes in these data are useful. These effects cannot be described simply for moderate numbers of channels but for large numbers of channels the effects are readily estimated from the change in the location of the asymptote shown on figure 7. The equation of this asymptote is as follows:

$$L = 10 \log_{10} N\tau + (V_0 + 0.115\sigma^2) + MPF + P_0 - 3 \text{ decibels}$$

where

L = test-tone load capacity
MPF = asymptotic multichannel peak factor
P_0 = long average power of a reference volume talker in decibels above 0.001 watt

The other quantities are as defined before.

Peak-Voltage Limiting

The curves referred to in the preceding discussion have so far neglected the effects of peak-voltage limiting in the transmitters and in the channel terminal equipment. Fundamentally, the effect of such limiting is to modify the distribution of instantaneous voltages in the individual channels. The extent of the modification, however, depends on the volume. For single-channel systems it is obvious that the improvement in load capacity due to limiting will be substantially equal to the reduction in the maximum peak voltage. For a large number of channels the improvement will approach the reduction in the rms voltage per channel. An approximate method of accounting for these complicated reactions is to consider that peak-voltage limiting modifies the upper end of the single-channel volume distribution. Strictly the amount of such modification is a function of the number of channels as well as of the characteristics of the limiters. Curve B of figure 1 represents a compromise between the different effects which is believed to give reasonably accurate results for both small and large numbers of channels for the limiting characteristic of present terminals.

With the talker volume distribution modified in accordance with curve B of figure 1, computations of the load capacity with voltage limiting present may be made in a manner identical with that previously described. Curve C of figure 7 shows the results obtained for this amount of limiting.

All of the load capacity curves of figure 7 are based on the equivalent volume which would be exceeded one per cent of the time, irrespective of the number of channels in the system. Where voltage limiting is used, it appears reasonable to consider this percentage as fixed because the action of the limiters serves to restrict the range of voltages above the overload point, thus reducing the severity of any overloading effects. When there is no limiting, and particularly for a small number of channels, the range of overloading voltage is not so restricted and overloading effects may become undesirably severe during the one per cent of time when the overload voltage is exceeded. If voltage limiting is not provided in some form, it may be important to reduce the percentage of time during which overloading may occur for small numbers of channels. This is a matter to be determined by experience and, if necessary, would require modification of curve B of figure 7 in the direction of requiring more load capacity for a small number of channels, thus increasing the spread between curves B and C.

Operating Margins, Etc.

The curves which have been given for output capacity versus number of channels apply to a single amplifier, or to a system in which all amplifiers are identical and work at the same output level without appreciable impairment of over-all performance. In practice, the number of amplifiers in tandem n a long system may be very large and problems of equalization and regulation may make it difficult to maintain exactly the same level conditions at all amplifiers. In addition, aging of tubes, and other effects will introduce some impairment. It is important, therefore, to allow a margin for these effects in the design of an amplifier for a multichannel system. The proper margin is essentially a matter of system design and it is often economical to build a liberal margin into the amplifiers in order to allow greater latitude and economy in the design of equalizing and regulating arrangements.

In addition to the speech loads, there are also impressed on the amplifiers various signaling and pilot frequencies, carrier leaks, etc. It is not always possible in practice to make these negligibly small and the load-capacity requirements must be corrected to allow for their presence. Multichannel telephone systems are also required to transmit other types of communication circuits, such as program channels and voice-frequency telegraph systems, superposed on one or more telephone channels. Modifications of the methods applied to speech loads may readily be made to determine the effect of these on the amplifier load capacity.

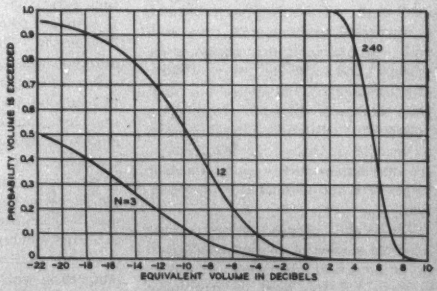

Figure 9. Equivalent volume distributions for systems of N channels

An Unstable Nonlinear Circuit

CLAUDE M. SUMMERS
ASSOCIATE AIEE

AN iron-core reactor in parallel with a capacitor in a series circuit with some kind of impedance will exhibit unstable characteristics under certain conditions. A change in one or more of the circuit parameters will cause the current or voltage associated with some element of the circuit to change suddenly from one stable value to another. Between these two conditions no value of current or voltage will satisfy all of the elements of the circuit simultaneously.

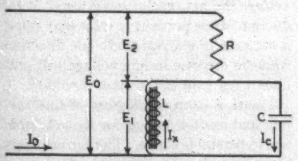

Figure 1. The parallel type of nonlinear circuit

The instability of certain types of circuits has been encountered in the past, especially on three-phase metering circuits. In general this is an undesirable condition, but there are several methods by which some practical use may be made of the unstable characteristics of the parallel reactor and capacitor circuit.

An accurate mathematical analysis of the circuit is very difficult because the exact equations of magnetic phenomena, and of the current and voltage wave forms, are quite complicated. Only a simplified theory is considered, and the discussion is based largely on the data taken on typical test circuits.

Circuit Characteristics

A circuit similar to figure 1 where the series impedance consists of pure resistance is the most simple form of the circuit. The measured characteristics of the reactor and capacitor as well as their combined volt-ampere curve are shown in figure 2. As the series resistance varies from a maximum to a minimum and returned to its highest value, at a constant line voltage, the voltage common to the reactor and capacitor follows the curve in figure 3. With decreasing values of resistance the voltage E_1 follows the curve VAX to the critical point X. A further incremental decrease in resistance causes the voltage suddenly to change from 49 volts to 102 volts and the line current likewise suddenly changes from 0.60 amperes to 0.14 amperes. If the resistance is further decreased, the voltage will continue along the curve YN, but if the resistance is increased the voltage will proceed along the curve NYZ to a second critical point Z where there is again a sudden readjustment of voltage—this time a collapse from 96 volts to 34 volts, and the current changes suddenly from 0.21 to 0.50 ampere.

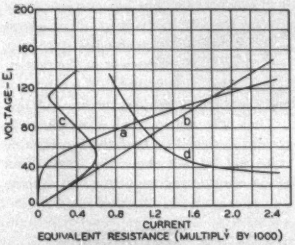

Figure 2. Characteristic curves of parallel branch of the nonlinear circuit, obtained from measurements

a—Reactor volt-ampere curve
b—Capacitor volt-ampere curve
c—Volt-ampere curve of combined reactor and capacitor
d—Equivalent resistance of reactor

Referring again to figure 3, the stable conditions along that portion of the curve VAX is called a substable state and is characterized by relatively low flux density in the reactor, good wave forms of current and voltage in all elements of the circuit, and by the line current leading the reactor voltage. After the circuit passes through the unstable period, stable conditions again prevail along the curve NYZ, which is called a hyperstable state. It has associated with it a relatively high flux density in the reactor, distorted wave forms, and in general the line current lags the reactor voltage.

Thus, there is a hysteresis-loop effect where the two critical points do not coincide. It has been found that the area within this hysteresis loop can be varied by changing one or more of several factors such as line voltage, the relation between the reactor and capacitor volt-ampere curves, or the equivalent resistance of the parallel circuit. The effect of varying the line voltage is shown in the group of curves in figure 4.

It has been observed that the unstable phenomena may be produced under certain conditions by a variation in any one or more of the quantities such as reactance, capacitance, series impedance, line voltages, or frequency. Thus, in the circuit considered above, figure 4 shows that instability will be encountered between 115 and 125 volts if the series resistance is fixed at 170 ohms. However, figure 4 also shows that the circuit will not become unstable for a variation in resistance or line voltage providing the latter never exceeds 100 volts. It is evident, therefore, that there are some factors that govern the instability of the circuit, and these can be understood more easily from a simple graphical analysis of the above circuit.

Circuit Theory

Figure 2 gives sufficient data to permit an approximate calculation of the instability curves as illustrated by an example in the appendix. The calculated curve in figure 5 indicates that the curve of series impedance has a maximum and minimum point, and that these agree reasonably well with the critical points of figure 3 for a line voltage of 125 volts. No correction was made for the distorted

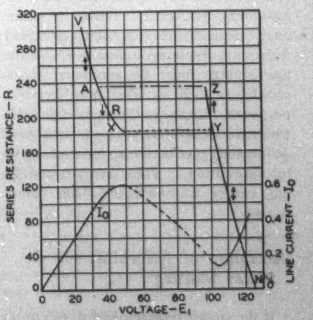

Figure 3. Instability curve for a line voltage of 125 volts

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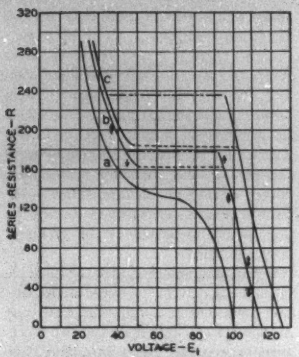

Figure 4. Effect of line voltage on instability

a—Line voltage 100 volts
b—Line voltage 115 volts
c—Line voltage 125 volts

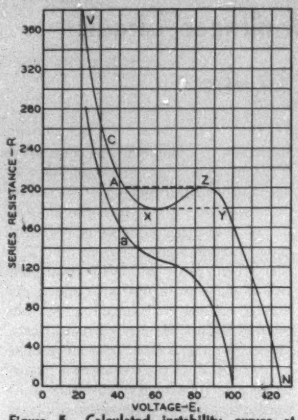

Figure 5. Calculated instability curves at line voltages of 100 volts (a) and 125 volts (c)

waves associated with the hyperstable condition, hence the greater discrepancy between the maximum and the critical point *Z*. The impedance curve for a line voltage of 100 volts does not contain maximum and minimum points; thus it may be concluded that the primary requisite for instability is that there must be such a relation between the various elements of the circuit that there will be a maximum and minimum point in the curve of series impedance plotted against the voltage common to the reactor and capacitor. Mathematically, the first derivative of an equation of R in terms of E_1 will show the presence of instability and the location of the critical points. If a different relation between the reactor and capacitor volt-ampere curves is chosen, the maximum and minimum points will occur at different values of series resistance and a different value of line voltage must be maintained before instability will occur. Thus, the reactance, capacitance, and their equivalent resistance, the series impedance, and the line voltage must be correlated if instability is to be avoided or deliberately produced. There are three probable fields where the characteristics of instability deliberately produced may have some useful application. These are phase shifting, energy transformation, and circuit control.

Utilization of Instability—Phase Shifting

If the circuit represented by the curves in figure 2 is applied to a line voltage 160 volts or higher, the highest value of E_1 in the substable range is about 55 volts. The capacitor current, curve *b*, is substantially greater than the reactor current at this point hence the line current, curve *c*, is leading the line voltage. The lowest value of E_1 in the hyperstable state may be 120 volts where current in the reactor is now greater than that in the capacitor and the line current lags the line voltage.

Thus, the line current in a nonlinear circuit, designed so that the hyperstable state will be well above the intersection of the reactor and capacitor volt-ampere curves, will shift from a large leading angle to a large lagging angle when passing into the hyperstable state. A reversing motor may be made by inserting this nonlinear circuit in series with one winding of a split-phase motor as in figure 6. A change in line voltage, or any other factor which will cause a shift from one stable state to the other, will cause a reversal of rotation. In fact, if the impedance of the series winding changes sufficiently with speed, the motor will continuously oscillate, first in one direction, then in the other. The number of revolutions in each direction depends on the value of line voltage, and at one value of voltage the net revolutions is zero. A reduction of one per cent or more may cause a net gain of revolutions in one direction while an increase in line voltage will produce a net gain in the other direction.

Figure 7 is an oscillogram of line current and reactor voltage for the substable and hyperstable states. The current leads the voltage by approximately 75 degrees and three cycles later it lags by about 60 degrees.

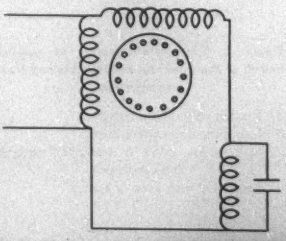

Figure 6. (above). Split-phase motor with unstable circuit

Figure 7. Oscillogram of transition from substable state (on left) to hyperstable state (on right)

Energy Conversion

A nonlinear circuit of a little different construction from those previously mentioned is shown in figure 8. The reactor not only acts as an autotransformer, but it acts as a solenoid to raise a plunger. Let the line voltage, frequency, series impedance, and capacitance remain con-

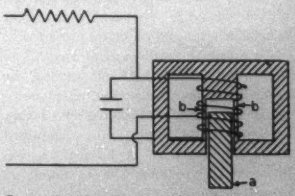

Figure 8. Arrangement of nonlinear circuit to produce reciprocating motion

a—Movable core *b*—Saturated section

stant and assume that the reactor operates in the substable state when the plunger is in the solenoid. The flux density in the reactor is low and the majority of the flux passes through the saturated section of steel, b. The small amount of flux passing through the plunger does not create a sufficient magnetic pull on the plunger to hold it against gravity or some other external force. Consequently, an external force will pull the plunger out of the solenoid and in doing so, the equivalent reactance of the circuit is changed sufficiently to cause the circuit to pass into the hyperstable state. The high voltage across the reactor then produces a sufficiently high flux to overcome the external force and the plunger moves into the solenoid. The forward motion of the plunger, however, causes the circuit to return to the substable condition, the attraction is released, and the external force again removes the plunger. Reciprocating motion is thereby produced and maintained as long as the motion of the plunger is capable of causing a transfer from one stable state to the other. The action is more easily understood from the hysteresis-loop characteristic curves in figure 9 where plunger displacement is plotted against magnetizing current in the reactor. This curve indicates a large difference between the attractive force for the inward and outward stroke.

If two similar reactors are connected by a common core as in figure 10, a continuously reciprocating system is obtained with power delivered during each stroke. In this circuit each reactor and capacitor group acts as a series impedance for the other. A reciprocating air compressor with a laminated iron core mounted on each end of the piston was inserted between two units. A pressure of 75 pounds per square inch was established in approximately two minutes in a container having a volume of 0.1 cubic foot, with the circuit oscillating at 240 strokes per minute. When the maximum pressure was obtained, the reciprocating motion ceased because the back pressure on the piston was equal to the magnetic attraction on the plunger. The power consumed under the stalled condition, was about one-fourth of its value when the unit was in motion. When the air pressure was reduced to a value sufficiently low for the attractive force to overcome this pressure and the static friction, the pump automatically started.

The frequency of the supply circuit affects the operation of reciprocating motion to some extent because it tends to change the period of oscillation of the plunger, and the area of hysteresis loop. For the circuit on which the tests were made, however, the frequency could be varied 20 cycles or more and the line voltage could be varied over a range of 100 per cent without causing the reciprocating motion to stop. The frequency of reciprocating motion depends not only upon the mechanical inertia but upon the electrical constants of the circuit. A change in capacitance or equivalent resistance in parallel with a nonlinear reactor will change the period of reciprocation within certain limits.

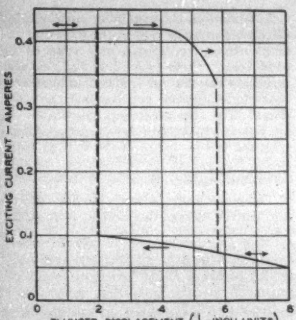

Figure 9 (left). Unidirectional pull on plunger of unstable circuit

Plunger moving into solenoid ⟶
Plunger moving out of solenoid ⟵

Figure 11. Oscillogram showing change in exciting current during motion of plunger

Top—Plunger moving out of solenoid
Bottom—Plunger moving into solenoid
E_0 = line voltage,
E_1 = reactor voltage,
I_x = reactor current

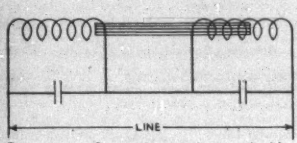

Figure 10. Circuit for producing double-acting reciprocating motion

Oscillograms in figure 11 show the rapid rate change of exciting current in the reactor when the core is suddenly withdrawn, and inserted.

A circuit similar to figure 8 may be used for electric bells, gongs, or signals without electrical contacts. The transformer A shown in series with the reactor and capacitor B in figure 12 is used instead of the ordinary bell transformer. The internal impedance of this transformer on open circuit is so high that instability cannot occur in the nonlinear circuit. When the secondary of the transformer is closed, however, the series impedance is reduced to a value which establishes reciprocating or vibrating mechanical motion.

Circuit Control

The nonlinear circuit may find many applications in controlling circuits but only a temperature control will be mentioned as an illustration.

The circuit shown in figure 8 may be a relay circuit in which a nonlinear re-

actor is used as the relay itself, that is, the plunger may carry the relay or circuit-breaker contacts. If the area of the plunger and saturated section are properly proportioned a continuous attractive force may be maintained instead of the reciprocating action. In other words, the motion of the core would not cause the system to change from one stable state into the other; but instability could be controlled by a variation in line voltage, series impedance, or some other suitable factor. A thermostat placed across the series resistance of the nonlinear reactor could control a power circuit without intermediate contactors or amplifiers. The important factor is that a small variation in the series impedance is amplified to produce a large and sudden variation in the voltage across the reactor which in turn influences the pull on the plunger.

A temperature-control circuit may be arranged as in figure 13 in which two series resistors have equal and opposite temperature coefficients of resistance. Tests on constant line voltage and frequency indicate that an increase of 0.4 per cent in one resistor and a corresponding decrease in the other resistor will cause the plunger to shift from the one reactor into the other. Thus, a temperature-control system could be operated without a thermostat or contact and would be relatively sensitive to temperature changes providing the line voltage and frequency remained constant. Two metals having practically equal and opposite temperature coefficients of resistance are titanium and zinc. The temperature sensitivity at constant line voltage and frequency in such a system would depend upon the value of temperature coefficient necessary to produce the required change in resistance. The 0.4 per cent change mentioned above would require a temperature change of less than two degrees centigrade to shift the plunger from one coil to the other if the series resistors were made of titanium and zinc. The effect of the line voltage and frequency depends upon the actual change occurring in series impedance. For example, if the temperature control system is set up as in figure 13 with a thermostat added as shown by the dotted lines, which short-circuits as much as 20 per cent of one resistor or the other; the effect of line voltage and frequency becomes negligible. An actual circuit operated satisfactorily over a 10-cycle change in frequency and a 20-volt variation in line voltage.

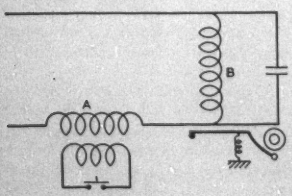

Figure 12. Unstable circuit for an electric bell without contacts

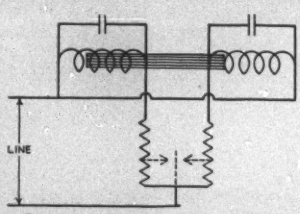

Figure 13. Temperature control circuit

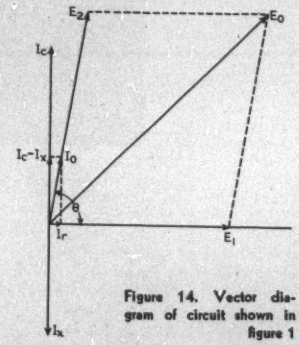

Figure 14. Vector diagram of circuit shown in figure 1

Summary

An instability curve of series impedance versus voltage common to the parallel branch of the circuit as in figure 1 can be calculated approximately. If this curve contains maximum and minimum points, the circuit will have two states of stability with an intermediate unstable range. Some practical use of this phenomenon has been suggested for circuit control and energy conversion. The circuit which produces reciprocating motion has not been completely analyzed, hence the optimum operating conditions cannot be stated until further knowledge is obtained.

Appendix

Any point on the instability curve can be calculated in figure 5 as in the following example which corresponds to a value of E_1 of 80 volts. From figure 2 we find that the measured line current I_0 is 0.42 ampere and that the equivalent resistance R_e is 1,090 ohms. The equivalent impedance is

$$Z_e = \frac{E_1}{I_0} = \frac{80}{0.42} = 190.5 \text{ ohms} \quad (1)$$

The phase angle between the line current and reactor voltage therefore is, from figure 14,

$$\cos\theta = \frac{Z_e}{R_e} = \frac{190.5}{1{,}090} = 0.175 \quad (2)$$

Since E_2 is a resistance voltage drop it is in phase with I_0, and the relation between E_1, E_2, and E_0 is, from figure 14,

$$E_1^2 + E_2^2 + 2E_1E_2\cos\theta = E_0^2 \quad (3)$$

Assume a line voltage of 125 volts. Then

$$(80)^2 + E_2^2 + 28E_2 = (125)^2 \quad (4)$$

from which

$$E_2 = 83 \text{ volts} \quad (5)$$

Then

$$R = \frac{83}{0.42} = 197.5 \text{ ohms} \quad (6)$$

When curves *a*, *b*, and *d* in figure 2 are available, the resultant current curve *c* can be calculated approximately as follows:

The component of current due to the equivalent resistance is

$$I_r = \frac{E_1}{R_e} \quad (7)$$

and

$$I_0 = \sqrt{(I_c - I_x)^2 + (I_r)^2} \quad (8)$$

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Theory and Design of NEMA Resistors for Motor Starting and Speed Control

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Synopsis: The National Electrical Manufacturers' Association classification of resistors for motor starting and speed control specifies the initial current peaks and the duty cycle for which the resistor must be designed. The nature of the load driven by the motor decides the valley current at which succeeding resistor steps must be switched in starting, and consequently the number of steps in the resistor, and points in the controller. The rms current, and the time each step is in the circuit, taken in conjunction with the cyclic current-carrying capacity of individual resistor elements, determines the selection of the elements on the basis of their continuous-current rating. It is usual to assume an rms current of 125 per cent, and switching at equal time intervals. However, in this paper, formulas are developed for more accurately calculating these values, and the formulas and necessary constants are tabulated. Consideration is given to d-c shunt and series-connected motors, and to wound-rotor a-c induction motors. Resistors for regulating duty are also discussed.

THE performance of any motor controller depends primarily upon the accuracy of the resistor design. A knowledge of the fundamental relations involved, and the theoretical basis and practical methods of resistor design are necessary to a clear understanding of motor control.

Resistor design has been simplified, and to some degree standardized, by a standard classification system. Such a system was adopted in 1917 by the Electric Power Club. The club was later merged into the National Electrical Manufacturers' Association, and the classification scheme became known alternatively as the American Engineering Standard or the NEMA standard system.

It was first based upon a four-minute duty cycle, but a few years ago was modified to conform more nearly with actual duty cycles most common in practice. The various classes are indicated by numbers. As originally used there were two figures in the class numbers, the first representing the duty cycle and the second the initial or peak value of the starting current. When the classification was revised, inasmuch as it was necessary to change the meaning of some of the figures, the number of digits was increased to three by the addition of the figure "1" before the two significant figures, to indicate the new classification.

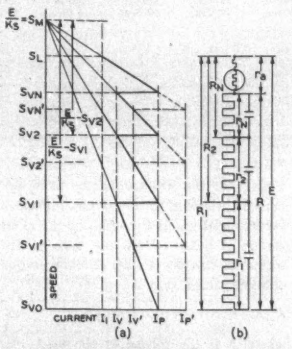

Figure 1

(a)—D-c motor speed-current relations with a NEMA starting resistor

(b)—Circuit connections

This classification, together with approximate starting torque, is given in table I.

Shunt-Wound D-C Motors—Total Resistance Value

On the first point of the controller, all of the resistance is in the circuit, the current rises toward a peak value determined by Ohm's law. However, as the motor starts, a counter electromotive force is developed in the armature which is proportional to the speed, and the current decreases toward a value which is just sufficient to develop the torque necessary to carry the mechanical load. The applied voltage, E, is at any instant exactly balanced by the sum of the resistance drop, ir, and the counter electromotive force so that, in a shunt-wound motor,

$$E = ir + K_s s \tag{1}$$

in which s is the speed, and the constant K_s may be evaluated by substituting for the other symbols the motor rated voltage, current, and speed, and the armature and lead resistance.

For current equal to zero, the second term vanishes, and the current-speed curves converge to the maximum theoretical speed, E/K_s, for all values of r, as shown in figure 1.

Now let it be assumed that the controller is arranged to cut out each succeeding step of resistance at the instant that the current decreases to a value I_v, and that the resistance steps are so proportioned that the current peaks are each equal to I_p, on the successive steps. Then the current-speed curves take the form shown by the heavy lines of figure 1a. As the total resistance takes the successive values, $R_1, R_2 \ldots R_n \ldots r_a$, at the successive instants of switching, the currents have become I_v, and the speeds $S_{v1}, S_{v2}, S_{vn}, \ldots$ etc. For any step, n,

$$E/K_s = I_v R_n/K_s + S_{vn} \tag{2}$$

From similar triangles

$$\frac{I_p}{I_v} = \frac{E/K_s - S_{vn}}{E/K_s - S_{v(n+1)}} = \frac{R_n}{R_{(n+1)}} \tag{3}$$

Let

$$X = I_p/I_v \tag{4}$$

Then $R_n = XR_{(n+1)}$, and the total resistance

$$R_1 = E/I_p = XR_2 = X^2R_3 = \ldots X^{(N-1)}R_N = X^N r_a \tag{5}$$

and

$$R_N = Xr_a \tag{6}$$

Let $r_1, r_2, r_3 \ldots r_N$ be the successive values of the individual resistance sections, numbered from the line terminal, as indicated in figure 1b, and let it be assumed that the resistance of armature and leads is expressed as a fraction, Z, of line voltage divided by rated motor current; that is:

$$r_a = ZE/I \tag{7}$$

It is standard practice to assume values for Z except in the case of very large motors, inasmuch as even quite a large percentage error will have little effect except in the current peak on the last point of the controller. For most motors 0.1 is a fair approximation.

Let the ratio of the current peaks to rated current be represented by Y. That is:

$$I_p = YI \tag{8}$$

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The values of Y for the various NEMA classes are indicated in the first column of table I, and are repeated in table II.

Also, let the external resistance, R_1-r_a, be represented by R. Then

$$R=UE/I \tag{9}$$

Here, U, defined by the equation, is, for $Z=0.1$.

$$U=1/Y-0.1 \tag{10}$$

It is the constant which when multiplied by the ratio of voltage to normal current gives the total ohmic value of the resistance for a particular application and class number.

The last step in the resistor is given by

$$r_N=R_N-r_a=R(X-1)Z/U$$
$$=R(X-1)/10U=C_rR \tag{11}$$

C_r is a constant defined by the equation.

The resistance of any other step, n, is

$$r_n=Xr_{(n+1)} \tag{12}$$

From equation 5 the number of steps in the resistor should be

$$N=\log\,(10/Y)/\log X \tag{13}$$

Inasmuch as N must be a whole number, this equation is necessarily used to determine X for assumed values of N, and the valley current can only approximate a desired value. *For the current peaks to be equal, and performance to be in accordance with the resistor design, the accelerating relays should be set to operate at*

$$I_p=IY/X \tag{14}$$

Values of C_r, U, and X are given in table II.

Accelerating Time

In order to determine the current-carrying capacities necessary for the successive resistor steps, it is necessary first to consider the variations of the motor speed with time. It is to be noted that the following assumptions are made.

1. Torque of the load is constant and less than the torque developed by the motor when carrying current equal to I_v.
2. The field excitation is constant.
3. The effect of inductance in delaying the rise of current, and hence, upon the peak value, is neglected.

The motor speed in radians per second is $2\pi s/60$, or $0.105s$.

The instantaneous torque is proportional to the instantaneous armature current, which in turn is given in terms of voltage and speed by equation 1. This torque is balanced by the sum of the torque of the motor load and the torque of acceleration, that is

$$K_t(E-K_gs)/r=0.105Jds/dt+L \tag{15}$$

where L is the torque of the load, r is the total circuit resistance at the particular time, K_t is a constant, which may be evaluated when the rate of acceleration ds/dt is zero, and $E-K_gs$ is equal to rI_L, the resistance drop at the current I_L required to carry the load. This gives L/K_t equal to I_L.

Hence equation 15 may be put in the form

$$\frac{ds}{dt}+\frac{K_tK_gs}{0.105Jr}=\frac{K_t}{0.105J}\left(\frac{E}{r}-I_L\right) \tag{16}$$

This is a linear differential equation the solution of which is

$$s=\left(\frac{E}{r}-I_L\right)r/K_g+C\epsilon^{-K_tK_gt/0.105Jr} \tag{17}$$

Table I. NEMA Resistor Classification Table

Per Cent Full-Load Current on First Point of Controller	Cycle and Corresponding Class Number: 30 Sec. on Out of 15 Min.	5 Sec. on Out of 80 Sec.	10 Sec. on Out of 80 Sec.	15 Sec. on Out of 90 Sec.	15 Sec. on Out of 60 Sec.	15 Sec. on Out of 45 Sec.	15 Sec. on Out of 30 Sec.	Continuous	Approximate Starting Torque in Per Cent of Full-Load Torque: Series Motors	Shunt Motors	Wound-Rotor Motors Three Phase
25	101	111	131	141	151	161	171	91	8	25	25
*50	102	112	132	142	152	*162	*172	92	30	50	50
70	103	113	133	143	153	163	173	93	50	70	70
100	104	114	134	144	154	164	174	94	100	100	100
150	105	115	135	145	155	165	175	95	170	150	150
200 or more	106	116	136	146	156	166	176	96	250	200	200

* Class 162 and 172 a-c mine-hoist resistors shall be designed for 33⅓ per cent current on first point of controller.

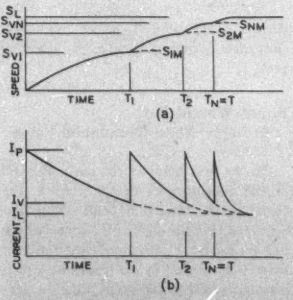

Figure 2

(a)—Speed-time curves for motor during acceleration

(b)—Current-time curves

t being time, ϵ being the base of the Naperian logarithms, and C a constant of integration, which may be evaluated by taking $t=0$ at $s=S_{n(n-1)}$ for the nth resistor step, when $r=R_n$, so that in

$$s=\left(\frac{E}{R_n}-I_L\right)\left[\frac{R_n}{K_g}+S_{n(n-1)}-\left(\frac{E}{R_n}-I_L\right)\frac{R_n}{K_g}\right]\epsilon^{-Kt/R_n} \tag{18}$$

which K is substituted for the constants in the exponential.

It is evident that $(E-I_LR_n)/K_g=S_{mn}$, the maximum speed attainable on the considered resistor step, so that

$$s=S_{mn}+(S_{n(n-1)}-S_{mn})\epsilon^{-Kt/R_n} \tag{19}$$

Thus, at time equal to infinity the speed curve becomes assymptotic to the ordinate S_{mn}. However, at some intermediate time, T_n, the current becomes I_p, and the accelerating relay causes switching to the next resistor step. This is shown in figure 2*a*.

Substituting into equation 19 the value of s obtained from equation 1 yields

$$i=I_L+(I_p-I_L)\epsilon^{-Kt/R_n} \tag{20}$$

This equation is graphically shown in figure 2*b*.

Let T_n represent the time in seconds on the nth step for the current to die from the peak to the valley value, and T the total starting period. Then from equation 20,

$$T_n = (R_n/K)2.3 \log_{10} (I_p - I_L/(I_s - I_L) \quad (21)$$

Hence

$$T_{(n+1)} = T_n R_{(n+1)}/R_n = T_n/X \quad (22)$$

Inasmuch as the total starting time is equal to the sum of the time on all steps, the time on the first step is given by

$$T_1 = T/(1+1/X+1/X^2+ \ldots +1/X^{N-1}) = TX^{N-1}(X-1)/(X^N-1) = C_T T \quad (23)$$

C_T is a constant defined by the equation. See table II.

Knowing the total starting time, equations 22 and 23 can be used to calculate the accelerating time on each step. *For time-limit acceleration the relays should be set so that the time ratio for the successive steps is equal to* X.

The total period the nth resistor step is in the circuit is $T_1+T_2+\ldots+T_n$. Let this be represented by P_n. Then,

$$P_n = T_1(1+1/X+1/X^2+\ldots+1/X^{(n-1)}) = T_1(X^n-1)/(X-1)X^{(n-1)} \quad (24)$$

The time of duty as given by the classification number does not necessarily give the starting period of the motor. Thus, in a 130 class instead of 10 seconds it may require but 5 seconds to start, with two starts in the 80-second period. However, the most severe condition for a given class is for a single start to occupy the whole of the allowed service time. Therefore, a resistor designed on this basis will be in every case adequate.

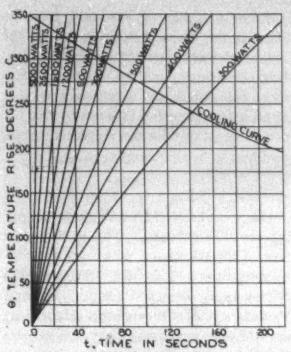

Figure 3a. Time-temperature curves for a starting resistor

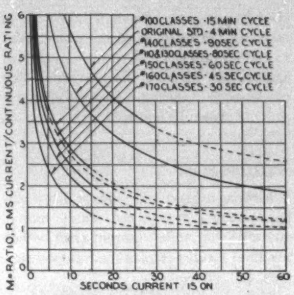

Figure 3b. Cyclic-capacity curves for a starting resistor, showing the ratio, M, of the short-time rms current to the continuous-current rating of the resistor elements, plotted against the time the current is on for the various duty cycles specified by the resistor class numbers

RMS Current

Often the current I_L required by the load during starting and the constant K in equation 20 may not readily be ascertained by the engineer who must lay out the resistor. For a given motor, resistor class, and number of steps, K and I_L are not mutually independent, however, and if I_L is fixed K is determined. The time for the current to decay from peak to valley value is fixed by the class number. Figure 5 shows a family of curves calculated for various assumed values of I_L. It is evident that the condition for highest rms starting current is for I_L to be equal to zero, and that this value does not differ radically from the rms value for most practical cases. On the assumption that I_L is zero, the rms current from equation 20 is, for the nth step,

$$I_{rms} = I_p \sqrt{R_n(1-\epsilon^{-2KT_n/R_n})/2KT_n} \quad (25)$$

As shown by equation 21, the ratio R_n/T_n is constant for all values of n, so that we may draw the very convenient conclusion that the rms current is the same for all steps. The value of T_n/R_n may be obtained by substituting 0 for I_L in equation 21. It follows that

$$I_{rms} = C_I I \quad (26)$$

where

$$C_I = I_{rms}/I = Y\sqrt{(1-1/X^2)/4.6 \log_{10} X} \quad (27)$$

Values of C_I for the various classes are given in table II.

Table II. Constants for Calculation of NEMA Accelerating Resistors for Shunt-Wound D-C Motors and A-C Three-Phase Wound-Rotor Induction Motors, Wye Resistor Connection

First two figures of class number		10	11	13	14	15	16	17
T (seconds)		30	5	10	15	15	15	15
Last Figure of Class Number:		**1**	**2**	**3**	**4**	**5**	**6**	
Number of Steps (N)	Y	0.25	0.50	0.70	1.00	1.50	2.00	
	$U_{D\text{-}C}$	3.9	1.9	1.33	0.90	0.57	0.40	
	$U_{A\text{-}C}$	2.2	1.0	0.77	0.52	0.32	0.23	
1	X	40.0	20.0	14.27	10.0	6.67	5.00	
	C_R	1.00	1.00	1.00	1.00	1.00	1.00	
	C_I	0.092	0.204	0.291	0.464	0.762	1.092	
	C_T	1.00	1.00	1.00	1.00	1.00	1.00	
2	X	6.325	4.472	3.3780	3.162	2.2582	2.236	
	C_R	0.1365	0.1824	0.2085	0.2402	0.2776	0.309	
	C_I	0.131	0.282	0.413	0.625	1.002	1.402	
	C_T	0.862	0.817	0.792	0.760	0.720	0.687	
3	X	3.420	2.714	2.427	2.154	1.882	1.710	
	C_R	0.0622	0.0902	0.1072	0.1282	0.1547	0.1775	
	C_I	0.1505	0.329	0.477	0.711	1.128	1.564	
	C_T	0.723	0.659	0.625	0.592	0.550	0.515	
4	X	2.515	2.115	1.944	1.778	1.607	1.495	
	C_R	0.0388	0.0587	0.0708	0.0865	0.1065	0.1237	
	C_I	0.1685	0.358	0.519	0.770	1.205	1.656	
	C_T	0.631	0.555	0.524	0.478	0.447	0.415	
5	X	2.091	1.821	1.702	1.585	1.461	1.380	
	C_R	0.0280	0.0432	0.0527	0.0650	0.0809	0.0950	
	C_I	0.1795	0.381	0.548	0.807	1.254	1.714	
	C_T	0.533	0.475	0.445	0.412	0.373	0.350	
6	X	1.849	1.648	1.558	1.468	1.373	1.308	
	C_R	0.0218	0.0341	0.0419	0.0520	0.0654	0.0770	
	C_I	0.1892	0.400	0.568	0.835	1.291	1.756	
	C_T	0.472	0.415	0.385	0.352	0.320	0.297	
7	X	1.695	1.533	1.462	1.389	1.311	1.259	
	C_R	0.01779	0.0281	0.0347	0.0432	0.0546	0.0647	
	C_I	0.1962	0.409	0.584	0.857	1.318	1.690	
	C_T	0.426	0.368	0.342	0.311	0.286	0.257	

Cyclic Capacity of Resistor Units

In order to apply table II to practical resistor design, it is necessary to know the cyclic capacity of the resistor elements. Such curves can be calculated from the dimensions and the physical and heat dissipation constants of the resistor. They may take the form of families of curves, showing the characteristics of each particular size of resistor element for various duty cycles, or inasmuch as these will be similar, may be

shown as one curve for each duty cycle in terms of the ratio M of the rms current to the normal element rating, I_e, plotted against the time P_s the particular step carries current during each cycle of operation, as shown in figure 3*b*.

SAMPLE CALCULATION

Assume a class 135 resistor for a 50-horsepower 230-volt d-c shunt motor, and that the valley current shall be not less than 100 per cent of the full-load current, 190 amperes.

Then $X = I_p/I_v = 1.5$ approximately.

Referring to table II, under the 5 class, it is seen that a five-step resistor (six-point controller) is required, the nearest value of X being 1.461. The corresponding value of U is 0.57.

The total resistance is $R = UE/I = 0.69$ ohm, and r_N is $C_rR = 0.0809R = 0.0557$ ohms. The resistances for the fourth, third, second, and first steps are determined by multiplying successively by X.

The duty cycle for the 130 class is 10 seconds on out of 80 seconds. Hence T is 10 seconds, and T_1 is $C_TT = 0.373 \times 10 = 3.73$ seconds. The rms current is $C_II = 1.254$ times full load, or 239 amperes. This divided by M, the I_{rms} to element rating ratio (4.17) read from the curve figure 3*b* for the 130 class at

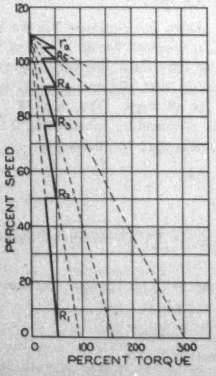

Figure 4a. Speed-torque curves for a five-step 2-class resistor, based on acceleration

3.73 seconds gives the element rating for the first step. The time on each point of the controller is determined by dividing the time on the previous point by X, and the "on" period is obtained by cumulative addition of those values, as shown in table III.

From a table of standard resistors (having the characteristics given by the curve) elements are chosen having continuous ratings equal to or greater than those calculated, and a sufficient number of each are connected in series to give the proper resistance for the respective steps.

REGULATING RESISTORS

Many of the NEMA resistor classes are inherently regulating. This is obviously true of the 90 classes, which are for continuous duty. The 150, 160, and 170 classes being designed for $^1/_4$, $^1/_3$, and $^1/_2$ duty cycles are evidently adapted to intermittent regulating duty. When on the first point of the controller they give currents greater than 100 per cent full load, the resistance and capacity for the successive steps may be laid out in accordance with the theory as previously outlined for accelerating resistors. However, with less than full-load current on the first step, they must be designed on a different basis. Consider for example a class 172 resistor having five steps.

In figure 4*a* are shown the speed torque curves laid out on the basis of acceleration with equal 50 per cent current peaks on all steps. It is evident that there can be little practical application for such a resistor, for the motor could operate only without load. However, for hoist duty, a high resistance on the first step is desired while taking the slack out of the hoisting cable. On subsequent steps, the resistor is required to give speed regulation while carrying full-torque load. With the resistor of figure 4*a* the load will not be started until the third point is reached, when 156 per cent torque will be developed, and a maximum speed of 42 per cent will be attained.

In figure 4*b*, is shown the speed-torque relation for a class 172 resistor based on speed regulation. Here approximately 120 per cent torque is available on the second point, giving a slow pickup, and a maximum speed of 20 per cent. The succeeding points give 50, 80, and 93 per cent speeds, respectively. The capacities of the various steps must necessarily be arbitrarily set at values which experience has indicated are adequate for usual conditions of service in regulating duty of this type.

A-C Three-Phase Wound-Rotor Induction Motor

In the case of an a-c wound-rotor three-phase motor, with the resistor wye-connected in the secondary, the speed, torque, and secondary-current relations are similar to those of the d-c shunt-wound motor. If in this case we let E and I represent the normal secondary voltage and current, respectively, the total resistance per phase is

$$R = E(1/\sqrt{3}Y - Z)/I = UE/I \qquad (28)$$

Assuming values of Z between 0.05 and 0.1, U takes the values given in table II.

Except for this different value of U, the calculation of the resistor is the same as for the case of the shunt-wound d-c motor.

If the resistor is delta connected the calculated resistance values should be multiplied by three and current values divided by $\sqrt{3}$.

Classes 162 and 172 a-c mine-hoist resistors, are modified by specific provision that the initial peak current shall

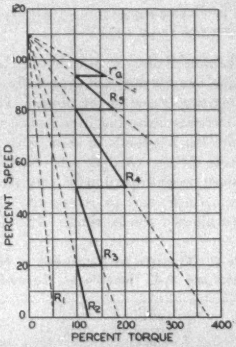

Figure 4b. Speed-torque curves for a five-step 2-class resistor, based on speed regulation

be $33^1/_3$ per cent of full load. The class 162 for vertical hoists is designed for 340 watts per horsepower, and the class 172 for slope hoists for 510 watts.

Acceleration With Unequal Current Peaks

If, instead of switching when the valley currents are I_v, the accelerating relays are set to operate at some other value I_v', then on all points after the first, the current peaks will be I_p', as shown in figure 1 From similar triangles,

$$I_p'/I_v' = I_p/I_v = X \qquad (29)$$

Let the ratio I_v/I_v' be represented by G. By symmetry, from equation 21, assuming $I_L = 0$ as before, we have,

$$T_1' = T_1(\log I_p/I_v')/\log I_p/I_v = AT_1 \qquad (30)$$

where

$$A = \log GX / \log X \tag{31}$$

Also, for $n > 1$,

$$T_n' = T_n(\log I_p'/I_e')/\log I_p/I_e = T_n \tag{32}$$

Hence, the time on all points of the controller may be calculated as in the previous cases, then the time on the first point modified by multiplying by A, and the period each resistor step is in the circuit obtained by cumulative addition.

On the first point, from equation 25, since from equation 21, $KT_1'/R_1 = \log GX$, the rms current is $C_{I1}'I$, where

$$C_{I1}' = Y\sqrt{(1-1/G^2X^2)/4.6\log_{10}GX} \tag{33}$$

For the other points, from equation 25, S. Solving for s at the instant of switching, when $r = R_n$ and $i = I_v$, and substituting this value into the equation with $r = R_{(n+1)}$ and $i = I_p$, we find that all steps have equal resistances,

$$r_n = R_n - R_{(n+1)} = R_1(X-1) = R/N \tag{35}$$

The desired valley current determines the number of steps, N. This is most conveniently used as a ratio, V, to full-load current.

$$V = I_v/I = Y/[1+1/(N+1)] \tag{36}$$

In practice it is customary to taper the resistance values of the steps a few per cent, the first being the highest, in order to minimize the effects of inequality between the resistance of the steps and that of the armature plus field and leads.

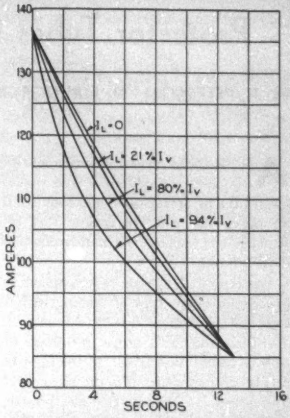

Figure 5. Curves showing the effect upon the current-time curve of varying the load component of the armature current, for fixed values of I_p, I_v, and T_1

Table III

Resistance Per Step	Accelerating Time		Period on Each Step	$M = I_{rms}/I_e$	I_e = Element Rating
$r_1 = 0.1750X = 0.2560$	$T_1 = 0.373T$	= 3.73	$P_1 = T_1 = 3.73$	4.17	57
$r_2 = 0.1196X = 0.1750$	$T_2 = 3.73/X$	= 2.545	$P_2 = P_1 + T_1 =$ 6.275	3.35	71
$r_3 = 0.0817X = 0.1196$	$T_3 = 2.545/X$	= 1.735	$P_3 = P_2 + T_2 =$ 8.010	3.01	79
$r_4 = 0.0557X = 0.0817$	$T_4 = 1.735/X$	= 1.185	$P_4 = P_3 + T_3 =$ 9.195	2.87	83
$r_N = 0.0809R = 0.0557$	$T_5 = 1.185/X$	= 0.805	$P_5 = P_4 + T_4 = 10.000$	2.75	87
0.6880		10.000			

Table IV. Constants for Series-Connected D-C Motors

Last Figure of Class Number	Y	U	Constant	Number of Steps 2	3	4	5	6	7
5	1.50	0.57	V	1.125	1.200	1.250	1.286	1.312	1.333
			C_T	0.500	0.333	0.250	0.200	0.167	0.143
			C_I	1.240	1.312	1.350	1.370	1.395	1.400
			C_T	0.500	0.333	0.250	0.200	0.167	3.143
6	2.0	0.40	V	1.500	1.600	1.667	1.718	1.750	1.780
			C_T	0.500	0.3333	0.250	0.200	0.167	0.143
			C_I	1.70	1.77	1.81	1.84	1.86	1.88
			C_T	0.500	0.333	0.250	0.250	0.167	0.143

since $T_n = T_n'$, and $I_p' = YI/G$, the rms current is equal to $1/G$ times the rms current for equal current peaks, or C_II/G.

The rms current for the complete period on any step is the weighted average for the time it is in the circuit.

Series-Wound D-C Motors

For series wound motors, the electromotive-force equation becomes

$$E = ir + K_s si \tag{34}$$

in which the constant K_s is determined at rated current, I, and rated speed, This is particularly necessary with small values of Y and N.

In the series motor, torque (neglecting saturation) is proportional to the square of the current, so that the torque equation becomes $i^2K_t = 0.105Jds/dt + L$, in which $K_t = L/I_L^2$, and the load is assumed constant. The solution is

$$t = 0.105JIEB/K_sL$$

$$B = 1/I_p - 1/i + \frac{1.15}{I_L}\log_{10}\frac{(I_p - I_L)(i + I_L)}{(i_p + I_L)(i - I_L)} \tag{37}$$

These being free from terms in r, indicate that the time and the rms currents are equal, respectively, on the several accelerating steps. The period any step is in the circuit is, therefore,

$$P_n = nT_n = nT/N = nC_TT \tag{38}$$

The rms current on each step is (for $I_L < I_v$)

$$I_{rms} = I_L\sqrt{1 + (1/I_v - 1/I_p)/B} \tag{39}$$

Here in the expression for B, $i = I_v$. (I_p must be greater than I_L.) For the 5 and 6 classes I_L is generally equal to the full-load current, I, and the constants for these classes are shown in table IV.

List of Symbols and Equations

Y = fraction of full-load current on first point
E = normal voltage
I = normal current
R = total ohmic value of resistor
X = ratio of peak to valley current
U, C_T, C_I, C_T, M, and V are constants evaluated in tables and curve
T = total time R is in circuit as defined by class number
N = number of resistor steps
$T_1 = P_1$ = time first resistor step is in circuit
P_n = time nth step is in circuit
r_N = resistance of last step
r_n = resistance of nth step
I_e = element rating
$R = UE/I$
$r_N = C_TR$
$r_{(n-1)} = Xr_n$
$T_1 = P_1 = C_TT$
$T_{(n+1)} = T_n/X$
$P_{(n+1)} = P_n + T_{(n+1)}$
$I_{rms} = C_II$
M = constant from figure 3b for P_n
$I_e = I_{rms}/M$

Protector Tubes for Power Systems

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AFTER eight years' experience with the design, application, and operation of the protector tube, it is considered an opportune time to review this experience and propose the standardization of this device.

Protector tubes have been applied to practically every type of system, with a total of approximately 50,000 now in operation and for a range in voltage of 13.8 to 230 kv inclusive. In the light of this broad experience it is the purpose of this paper to summarize the present conception of the theory of the operation, the factors that should be considered in the characteristics of the device, the characteristics of the system, and then suggest a standardization of the device to simplify its application. This joint paper was undertaken at the request of the lightning-arrester subcommittee of the AIEE protective-devices committee.

Theory of Tube Operation

Since the protector tubes are to prevent flashover of line insulation the prime requirements are that their discharge voltage be lower than the flashover voltage of the insulation which they are protecting and they must also be capable of interrupting the generated follow current. Operation may be more readily understood by first considering the phenomena involved in current interruption. After the surge currents are discharged to ground, the normal-frequency or generated current may follow and in order to have satisfactory operation, the protector tube must have a rate of insulation recovery after generated-current zero greater than the rate at which the system voltage recovers. This can best be explained by considering the recovery voltage on a simple circuit.

Such a circuit shown in figure 1 possesses the basic elements required to illustrate the transient recovery voltage, following interruption of fault current. This circuit contains lumped constants of L, R, and C in such proportion that it will have a natural frequency of oscillation. When a fault is placed at F and later removed at a normal-current zero, an oscillating voltage will appear across the capacitor, which will be composed of the normal-frequency voltage and a voltage whose frequency corresponds to the circuit's natural frequency. The simplest method of developing the oscillating voltage is to consider the generated voltage and oscillating voltage separately. At the instant the fault is removed, the voltage across the fault must be zero. This condition of zero voltage is satisfied if it is assumed that there is a natural-frequency voltage that appears instantly equal and opposite in magnitude to that of the generated voltage. The sum of these two voltages V_R is therefore the recovery voltage of the circuit. The time to crest of the oscillation is approximately proportional to $\sqrt{LC}$. Therefore if either L or C is increased, the time to the recovery-voltage crest of the natural-frequency oscillation will increase. This conception is important as the L of the source and C of the line vary for different line conditions. Theoretically, the natural-frequency voltage will start equal to the generated voltage at the instant the fault is removed assuming no losses, and oscillate about this voltage as an axis. However, losses produce damping and this natural-frequency component will decay at a rate depending upon the losses in the circuit.

When a protector tube is discharged by lightning and power follow current flows through the tube, it must have the properties of changing from a good conductor to a good insulator for satisfactory operation. In any interrupting device it takes time to establish the insulating characteristics which are commonly called the insulation recovery characteristics of the device. The interruption is therefore a race between the insulation recovery strength of the device and the voltage recovery on the system. Curve A of figure 2 is the recovery voltage for a more complicated system. Instead of having simple oscillations as in figure 1 the recovery voltage is now a more complicated function of time as the result of a succession of traveling waves on the line.

Curves B, C, and D of figure 2 are hypothetical insulation-recovery curves for a protective device. If the protective device has the characteristics shown in curve B and the system recovery characteristics are as shown in curve A, then the interruption will be satisfactory, as the insulation recovery of the device is faster than the voltage recovery on the system. On the other hand, if the protective-device insulation recovery strength is as shown in curve C or curve D, then the system recovery voltage overtakes the insulation recovery strength at second or first crest, respectively, restriking will take place, and if this occurs at more than two consecutive current zeros, the operation is in general not considered satisfactory. It is therefore possible to predetermine the operation of tubes on a system by comparing the insulation recovery strength of the tube and the system recovery voltage.

The protector-tube insulation-recovery curves and the voltage-recovery curves will vary for each current value. For a

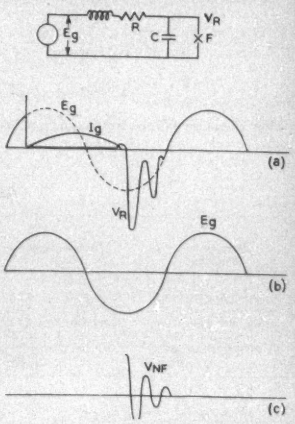

Figure 1. Elements of recovery voltage

E_g —Generated voltage
I_g —Generated current
V_R —Protector-tube voltage
V_{NF} —Natural-frequency voltage

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given short-circuit current the protector-tube insulation-recovery curves also are lower with increased bore. Thus if the protector tube, when new, starts with a characteristic such as shown in curve *B*, figure 3, as it erodes the bore will increase and the curve will drop until at curve *C* it will fail to give satisfactory interrupting characteristics. It is for this reason that the rate of erosion must be considered in protector-tube design. Likewise, the same tube will have different insulation-recovery curves for different values of current. Curve *A*, figure 4, may be the insulation recovery strength for maximum current, and the insulation recovery strength for minimum current might be of the order of curve *B*, of this figure. Thus the system recovery-voltage curves must be compared with the insulation recovery strengths of the protective device to see that operation will be correct. The following discussion

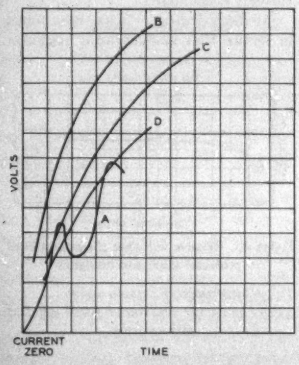

Figure 2. Elements of protector-tube operation

A—Recovery voltage of complex system
B, C, D—Protector-tube insulation recovery curves

will therefore deal with system characteristics and protector-tube characteristics showing how this has been done to arrive at a standard line of protector tubes.

System Characteristics

General Consideration

Since protector tubes are connected between line and ground, it is necessary that the system characteristics which affect tube performance be determined as viewed from the tube location. It is therefore obvious that to make a successful application the single, double, and triple line-to-ground follow currents and corresponding recovery voltages must be evaluated.

A number of factors will determine the magnitude of the currents and the associated recovery voltages. For example:

1. Method of grounding the system neutral, that is, solid grounding, resistance or reactance grounding, or any combination of these.
2. Minimum and maximum connected system capacity (variation in operating conditions).
3. Length of connected circuit or lines in miles and relative location of short-circuit-current sources.
4. Line configuration and presence of overhead ground wires.
5. Tower-footing resistance.
6. Protector-tube location.

(*a*) *Determination of the Short-Circuit Current Range*

The three-phase short-circuit current is in general the maximum current obtained, except near the system grounding points where the line-to-ground current may be greater. The single-line-to-ground current should be determined both with and without the effects of tower-footing resistance.

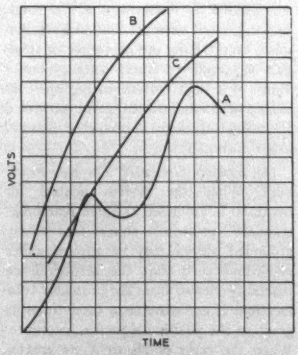

Figure 3. Effect of erosion on protector-tube operation

A—Recovery voltage of complex system
B, C—Protector-tube insulation recovery

The double-line-to-ground currents will usually be between the values obtained for single-line-to-ground and triple-line-to-ground faults. However, there may be exceptions for low ratios of zero to positive-sequence reactance and for high values of circuit resistance. Usually, such deviations are quantitatively unimportant.

Where the line is long or the system is extensive and the short-circuit currents vary widely, the application of tubes can be helped by plotting a current profile of the line (or lines) and zoning the tubes. Figure 5 shows such a profile for an assumed system. It may be noted that the maximum currents are at the generating and system ground points, which is usually the case for a solidly grounded-neutral system. By zoning the tubes it is possible to use tubes having a lower maximum rating in many locations, thereby obtaining tubes capable of operating successfully on lower currents or with higher tower-footing resistances.

When possible, it is desirable to take into account future system growth and its effect upon the currents to which the tube may be subjected.

While it is necessary to determine both the maximum and minimum currents that the tube may be called upon to interrupt, it is equally and perhaps more important to evaluate the currents expected under normal conditions. In doing this it may become quite evident that a particular system condition is imposing altogether too severe restriction on the tubes relative to the probability of that condition being obtained. The system condition which comes under this classification may occur when part of the system is temporarily disconnected.

When determining short-circuit currents it is only necessary to determine the rms symmetrical short-circuit current, as the design of the tube is such as to allow for the maximum asymmetrical current which may normally be expected in a power circuit. Since protector tubes

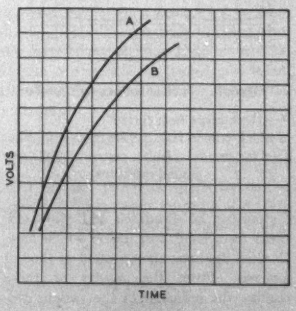

Figure 4. Effect of current on protector-tube operation

A—Tube insulation recovery, maximum current
B—Tube insulation recovery, minimum current

usually interrupt within the first cycle, subtransient values of synchronous-machine reactances should be used in current calculations. For fault locations which are remote electrically from large rotating equipment, generators, or synchronous condensers, it may be necessary to consider the effect of rotating motor loads as both synchronous motors and induction motors will contribute short-circuit currents. In general, this is an important factor only when the tubes are located electrically at some distance from the source of system supply or generation. The method of symmetrical components may be used for the calculation of the short-circuit currents. A-c network calculators or network analyzers may be used to advantage when available. These methods are well known and are fully described in the literature.

(b) System Recovery Voltage Characteristics

It has been shown above that the tube's dielectric-strength recovery must exceed the system voltage recovery in order to prevent a restrike in the tube and possibly failure to interrupt.

It is evident that in general the complete voltage-recovery characteristic is necessary in order to determine tube performance. The effect of system characteristics on the voltage-recovery characteristics has been given a great deal of study,[1-4] particularly by the use of miniature or equivalent systems. By this method, the effect of the various system

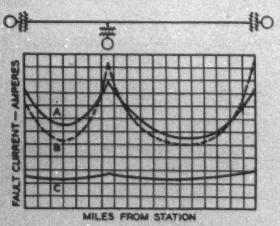

Figure 5. Typical fault-current profile

A—Three-phase fault current
B—Line-ground fault current (zero resistance)
C—Line-ground fault current (100-ohm ground resistance)

factors can be simulated and evaluated. Field tests have been made which have checked the equivalent system method of analysis. From the results of these studies, the influence of the various system factors can be evaluated and tube applications made accordingly.

1. For all numbered references, see list at end of paper.

(1) *Solidly Grounded Systems.* The solidly grounded system which has all sources of short-circuit current solidly grounded, is a representative type of system found particularly at the higher voltages. The effect of tower-footing resistance is to reduce the current and to reduce the magnitude of recovery voltages across the tube. This resistance reduces the recovery voltage on account of the improvement of the power factor in the circuit which means that at current zero or time of interruption, the instantaneous fundamental-frequency voltage is of lower magnitude than for a pure reactive circuit. However, there is a lower limit to which the current can be reduced and still have successful operation. The limits will be discussed later in this paper.

(2) *Systems Grounded Through Resistance.* For practical purposes the effect of system neutral resistance is similar to the effect of tower-footing resistance discussed above. In cases where both neutral-grounding resistance and tower-footing resistance are encountered, they should be considered as being in series. Thus the same limits apply as pointed out for solidly grounded systems with tower-footing resistance alone. If the sum of those resistances is such that a single protector tube does not have the current range to interrupt both the phase currents not limited by resistance and the single line-to-ground currents limited by resistance, then the use of four protector tubes can be considered where three protector tubes of a high current rating are connected in star and the star point connected to ground through a protector tube of lower current rating.

(3) *Systems Grounded Through Reactance.* When the system neutral (or neutrals) is grounded through reactance, standard protector tubes for solidly grounded service may be applied under conditions such that the zero-sequence reactance viewed from the protector tube locations is not more than three times as great as the positive-sequence reactance. When the ratio of X_0 to X_1 is greater than this special consideration must be given to the protector tube. However, in a large number of cases the protector tube for the next higher voltage rating will be applicable. When the protector tubes are used on a system using a tuned value of reactance or using a ground-fault neutralizer, the line-to-ground currents should not have to be cleared by the tube. Thus protector tubes built for line-to-line voltage can be applied on the basis of the line-to-line fault currents only.

(4) *Isolated-Neutral System.* Protector tubes applied on an isolated-neutral system must be given special consideration, as the single-line-to-ground current (charging current) will usually be below the minimum current rating for the suggested standard tube. In connection with the application of protector tubes to isolated-neutral systems consideration should be given to the four-tube scheme as such a scheme should ease the problem of interrupting charging current.

(5) *Lightning Severity.* Investigations indicate the possibilities of lightning strokes of the order of 200,000 amperes although the probability of getting a stroke in excess of 100,000 amperes is very remote as indicated by actual field data. Furthermore, several tubes may share the lightning discharge current with the result that the duty on each tube is reduced. Operating experience with protector tubes over an eight-year period indicates that the existing designs are adequate for the vast majority of surge currents encountered.

(6) *Relay Settings.* It has been found in service that systems using protector

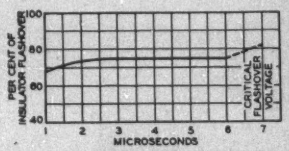

Figure 6. Relative volt-time characteristics of protector tubes and insulators

$1\frac{1}{2}$x40-microsecond positive wave
115-kv protector tube versus seven standard disk insulators

tubes should not have relay settings less than two cycles. Where relays have a shorter operating time, it will be necessary to introduce a delay to prevent unnecessary circuit outages.

Protector-Tube Characteristics

(a) Impulse Protection Level

Since the protector tubes are used to prevent the flashover of line insulators, their primary characteristic must be a discharge-voltage value lower than that of parallel insulators which they protect. This requirement naturally serves to limit the length of the protector tube between electrodes. The devices are installed with an air gap in series, provided for the purpose of withstanding the normal impressed voltage to avoid possible corona or leakage currents across the protector tube itself. In general, the spac-

ing of this air gap is considerably less than the spacing between the protector tube electrodes. Consequently, this series air gap will not add greatly to the over-all discharge voltage value of the applied protector tube. The impulse-discharge voltage level of protector tubes is best shown in the form of a volt-time curve. Such curves have been generalized for protector tubes, a typical curve being shown in figure 6 for the positive $1^1/_2$x40-microsecond wave. It should be noted

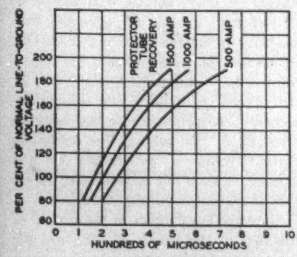

Figure 7. Effect of current on recovery voltage of protector tube

that the volt-time characteristic of the protector tube is flatter than that of insulators.

As illustrated in figure 6 it can be shown that where the protector tube gives protection to an insulator on the positive $1^1/_2$x40-microsecond wave at the critical flashover point, the protector tube will in general also protect for waves rising to flashover in shorter times or on negative polarity. Therefore, a comparison of the margin existing between the protector tube and the insulator based on the $1^1/_2$x40 positive wave may be taken as a yardstick for determining whether or not a sufficient margin exists between the level of the protector tube and the insulator. To aid in the application of protector tubes, table I has been prepared to show the discharge level of protector tubes. The table includes the minimum tight-string metal-to-metal arcing distance which the tube is expected to protect. These values include a factor of ten per cent between the actual discharge voltage of the protector tube and the impulse flashover voltage corresponding to the dry arcing distance. It is felt that 10 per cent represents the minimum margin which should be used in any case. Sufficient clearance should be provided between the protector tube and the structure to which it is attached to assure that lightning flashover will be confined within the protector tube.

(b) Tube Interrupting Characteristics as Affected by Voltage, Current, Time

It has been shown in previous papers presented to the Institute that for a given design the ability of a protector tube to function properly is a function of voltage and time for a fixed current. Likewise, this characteristic varies with the magnitude of current through the tube. These properties are illustrated in figure 7.

(c) Effect of Bore and Tube Erosion

When the protector tube operates, a part of the fiber wall is volatilized, creating a stream of rapidly moving gases which quench the arc. This volatilization of the fiber results in an increase in the tube-bore diameter. As the bore of the tube increases in diameter, the clearing characteristics of the tube undergo a change, the effect being to increase the required clearing current for any fixed recovery voltage. Figure 8 shows how the minimum clearing current of a particular protector tube increases with bore. It may be noted in this curve that an increase in the bore diameter of approximately 30 per cent doubles the minimum current that can be cleared.

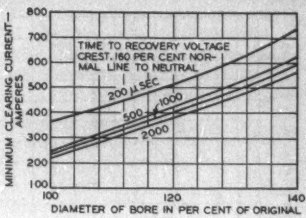

Figure 8. Effect of erosion on minimum current required for interruption

Where protector tubes are installed at every structure along the line, the probability of any protector tube having to operate a large number of times is greatly reduced, as compared to a protector tube applied at a reflection point. Over a five-year period on such a line, out of a total of 810 protector tubes, 228 tubes will operate once, 63 twice, 13 three times, 8 four times, 0 five times.[5] Also, the records of erosion of protector tubes over a six-year period on a particular line[6] indicated that no protector tubes had reached the limit of useful life. An inspection of these results leads immediately to the conclusion that where protector tubes are installed on every structure, the erosion of the bore from the standpoint of operations will not constitute a limiting factor as far as protector-tube life is concerned.

In other types of installation, such as river-crossing towers or terminal structures of lines which are not completely equipped throughout with new protector tubes, the tubes which are installed at these points will be called upon to operate more frequently. In such cases, a record should be kept both of the number of tube operations and the erosion occurring in the protector-tube bore, as it will be possible from these records to determine the time when the maximum permissible erosion of the bore is reached and when therefore the protector tube should be replaced.

(d) Impulse-Discharge-Current Capabilities

In general, protector tubes can withstand lightning-stroke currents of 50,000 to 100,000 amperes on the basis of a current wave that rises to crest in 10 microseconds and decays to half value in 20 microseconds. Experience to date with thousands of protector tubes has shown that the probability of a protector tube being burst from lightning current in excess of its discharge capabilities is small. It therefore appears that the

Table I

Circuit Voltage Rating	Tube-Discharge Critical Voltage, Representative Value Dry,* $1^1/_2$x40 Wave		Protector-Tube Impulse Discharge-Voltage Characteristics		
	Positive	Negative	Series Gap† (Inches)	Minimum Dry Arcing Distance Tube Will Protect (Inches)	Number Standard Insulator Disks Tube Will Protect; $5^3/_4$ by 10-Inch Spacing
13.8	100	110	$^3/_4$	6	1
23	150	155	$1^1/_2$	9	2
34.5	200	220	2	$12^1/_2$	2
46	260	285	$3^1/_4$	17	3
69	375	420	$5^1/_2$	28	5
92	475	540	$8^1/_2$		6
115	575	635	11		7

* Actual values will vary somewhat, depending on the design and mounting of the tube.

† These are recommended minimum series gaps. Under no conditions of operation should the series gap be less than 80 per cent of the recommended minimum.

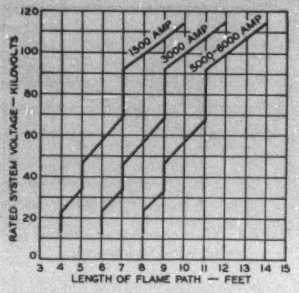

Figure 9. Visible flame path as a function of power, current, and voltage

impulse-discharge capabilities of protector tubes are sufficient to withstand all but the most severe direct strokes.

(e) Effect of Weather

Insufficient time has elapsed since the protector tubes have been in service to form a definite opinion as to the ultimate life expectancy from the standpoint of weathering. The outside finish on tubes has been improved. The experience, with modern finishes, indicates good weathering characteristics. The exact performance will depend on the local atmospheric conditions. Periodic refinishing of protector tubes with a good paint will increase their weather resistance.

(f) Discharge Gases and Recoil Forces

The ionized gases must be properly directed to avoid flashovers due to their conductivity. Figure 9 shows the length of the visible flame path as a function of the power current and voltage. Obviously, the circuit voltage and the protector-tube dimensions should be considered when establishing the safe strike distance from the gas envelope to the object of different potential.

Recoil forces must be considered when designing the mounting hardware. It is of importance that the mounting hardware be designed to facilitate ease of installation. This results in a direct saving to the operator, and broadens the field of application of the device.

Proposed Standard Protector Tubes

In order to facilitate the application of any device, it is desirable to have standards. This very aptly applies to the protector tube because of the large number of variables that enter into its application. It is for this reason that considerable thought has been given to the requirements for such a standardization. Based on the large amount of work done on miniature systems and eight years experience with the operation of protector tubes in the field, requirements for a proposed line of protector tubes are presented in table II.

When establishing the requirements for a standard line of protector tubes, it is necessary to select system conditions having recovery-voltage characteristics of sufficient severity to cover the vast majority of applications and from this determine the tube design. The maximum rating of the protector tube may be determined by either the insulation-recovery characteristics or the bursting strength of the tubes. The minimum current rating is determined by the amount of allowable erosion after operation at maximum current rating.

Since the capacitance of the system (a function of the length of line) and the reactance of the system are the major factors in determining recovery-voltage conditions of the system, it is essential to fix some minimum length of line which establishes the maximum permis-

Table II. Recovery-Voltage Characteristics for Which Proposed Standard Tubes Are Designed

System Kilovolts	Minimum Miles of Line*†	Tube Current Rating**		Minimum Current, Maximum Significant Crest		Maximum Current			
						First Crest		Maximum Significant Crest	
		Minimum	Maximum	Per Cent Voltage	Time (Microseconds)	Per Cent Voltage	Time	Per Cent Voltage	Time
13.8	10	300	1,500	160	230	90	55	165	130
		400	3,000	160	230	90	35	160	120
		600	6,000	160	200	90	25	160	120
23	15	300	1,500	165	400	73	65	165	250
		400	3,000	165	400	86	45	160	190
		600	6,000	165	400	94	30	158	190
34.5	22.5	300	1,500	170	600	65	80	165	390
		400	3,000	170	600	85	60	159	270
		600	5,000	170	600	100	50	156	270
46	30	300	1,500	165	800	70	115	165	530
		400	3,000	165	800	90	80	159	370
		900	6,000	165	750	105	70	153	330
69	45	400	1,500	165	1,100	85	180	165	800
		600	3,000	165	1,100	105	140	158	590
		900	5,000	165	900	115	100	149	490
92	60	400	1,500	160	1,300	88	240	165	1,070
		600	3,000	160	1,300	104	220	157	930
		1,000	5,000	160	1,100	115	180	145	760
115	75	500	1,500	160	1,450	90	300	165	1,350
		600	3,000	160	1,450	98	300	156	1,270
		1,000	5,000	160	1,350	105	300	140	1,100
138	90	500	1,500	160	1,600	90	350	165	1,440
		600	3,000	160	1,600	90	350	155	1,320
		1,000	5,000	160	1,500	90	390	136	1,250

* Miles listed are the minimum circuit miles of overhead line connected or equivalent where the line has a single source of short-circuit current at one end. Cable should be reduced to the equivalent miles of overhead line as indicated in figure 10.

† When two sources of short-circuit current are available, the miles of line in column 2 should be increased by a factor K determined from figure 11. If less miles of line between sources are available than required by the use of figure 11, but more than shown in column 2, then a detailed calculation is necessary for the application.

** Guide for application when minimum current is limited by resistance.

The minimum current rating which is assigned to standard protector tubes is based on the short-circuit current through the tube being limited predominantly by inductive reactance. The protector tubes will actually interrupt currents as low as 85 per cent of their minimum name-plate rating for circuits 69 kv and above or 70 per cent of their minimum current rating for circuits 46 kv and below, where circuit resistance (tube grounding resistance) is included, provided the calculated minimum current neglecting all resistance is equal to or greater than the tube's minimum name-plate rating.

sible severity of recovery voltages. It was recognized in selecting a suggested list of standard ratings that they would not cover all the possible applications. However, it was felt that a balance could be obtained between the circuit requirements and the design limitations of the protector tube which would cover the majority of applications. Weighing all factors, the miles of line listed in table II for each operating voltage were believed best suited. Lines shorter than those listed tend to give rise to more severe recovery-voltage characteristics than are generally encountered. With the system conditions listed in table II the corresponding recovery-voltage characteristics have been obtained from the studies already referred to and requirements for a protector-tube design determined so that the protector tube can operate and still have the dielectric-recovery curve above the system recovery voltage, or in other words, have successful operation of the device. Since rate of rise of recovery voltage immediately following interruption is essentially proportional to current, the significance of the first crests of the voltage-recovery characteristics is not as great for minimum current ratings as it is for maximum current ratings. Therefore, only one point is defined on the system recovery characteristics for protector-tube minimum current ratings while two points are defined for maximum current ratings. Since the majority of protector tubes are applied on solidly grounded-neutral systems, it was felt that this should be the basis for the standard design. Other methods of grounding will be dealt with either by the use of application factors to allow the selection of a standard protector tube for use on the special system or the design of a special protector tube.

Based on the above general thoughts, the following application guides are suggested for consideration in the standardization of this line of apparatus.

(a) Basis of Design

Protector tubes are designed to withstand one operation for tubes rated at 5,000 and 6,000 amperes, two operations for tubes rated at 3,000 amperes, and three operations for tubes rated at 1,500 amperes, at maximum rated current with fully offset current wave after which the protector tube will be required to clear two operations at minimum rated current and with the associated recovery voltage. The tube performance is based on interruption of the current actually obtained during the one test at maximum rated current in less than $^1/_{60}$ second and the minimum rated current in less than $^1/_{40}$ second.

The maximum symmetrical nameplate rating in table II is based on the maximum crest current which the tube will stand divided by a factor of not less than 2.5 to take into account the effect of asymmetry. The minimum symmetrical rms current rating is based on the minimum crest current divided by 1.41 to convert to rms amperes.

(b) Discussion of Standard Ratings

It is felt that the requirements set forth in table II are suitable for consideration for standard ratings. A review of the actual field experience with a large number of protector tubes indicates that although the tubes are designed for these very severe conditions, actual system conditions are very much less severe. For example, there are not many systems that have as few miles of line as the minimum selected. This means that recovery voltages on actual systems are generally less severe and therefore a greater number of operations or a greater amount of erosion is permissible. Likewise, the requirements are based on a completely offset wave with the low value of damping of the d-c component. The probability of securing the completely offset wave is low and also the damping on the actual system is usually higher than assumed. The rate of erosion is dependent on the magnitude of current. For example, a standard-design tube for a 34.5-kv system might have 25 mils erosion for each operation with maximum current completely offset as used for the design requirements whereas for minimum current it will take several operations before any similar erosion is found. Since tubes are applied for maximum system generation connected, any reduction in this item will reduce the short-circuit current when the tube operates and therefore reduce the rate of erosion.

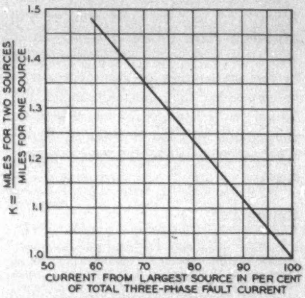

Figure 11. "K" factor for lines with two sources

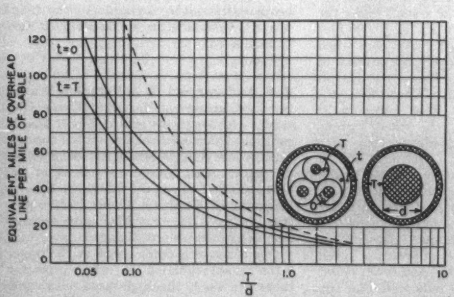

Figure 10. Overhead-line equivalent of cables

Dashed curve—Single conductor

Solid curves—Three conductors

For paper-insulated cable assumed dielectric constant 3.8

For varnished-cambric or rubber insulation multiply by 1.35

Overhead-line equivalent based on positive-sequence capacity, susceptance of 6.0 micromhos per mile

(c) Standard Tubes Operating at Reduced Voltage

Where the minimum line-to-ground current of the circuit is below the minimum current rating assigned to standard tubes, and the insulation of the circuit is high enough to permit the use of a tube having the next higher voltage rating, this higher-voltage protector tube will interrupt lower than the listed minimum current.

To determine the minimum current which the protector tube will interrupt when used on a circuit below its voltage rating, multiply the normal minimum current rating of the protector tube by the ratio of the lower operating voltage on which the device is to be used to the normal voltage rating of the protector tube. This lower value of current can

be considered as being limited by reactance only and applied in the same way standard tubes are applied.

Conclusions

In view of the large amount of analytical work and the eight years of field experience with protector tubes, all of which has been taken into consideration in the preparation of this paper, it is recommended that the information contained in this paper be considered in conjunction with the proposed protector-tube standards as a basis for their application.

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5. Discussion of Sporn and Gross paper by E. J. Wade. AIEE Transactions, volume 57, 1938 (September section), page 528.

6. Experience With Protector Tubes, E. Wisco and A. C. Monteith. *Electric Journal*, August 1938, page 299.

Discussion

M. C. Westrate (The Commonwealth and Southern Corporation, Jackson, Mich.): The paper covers the installation of protector tubes on transmission lines only, and does not mention their use for station application. We believe, however, that there is a definite application for protector tubes on line entrances to substations for protection of air switches and oil circuit breakers in open position. The simplicity with which these tubes can be installed has made it possible for us to install them for less cost than plain rod gaps in some cases. We have carefully engineered all our applications of protector tubes, and the experience has been very satisfactory both on 44-kv isolated-neutral and 22-kv grounded-neutral systems. We are now installing some at stations on a 140-kv grounded neutral system.

On the isolated-neutral system, we have used only the three-tube scheme with tubes of the same rating as for a grounded-neutral system. The problem on isolated neutral systems is usually that single line-to-ground faults do not produce enough current for satisfactory expulsion action of the tubes; however, if the system is not too large, the current may be low enough to interrupt itself without this action.

It was indeed a surprise to learn that protector tubes should be designed for such a limited life as one, two, or even three operations. A further explanation of this would be appreciated since it does not agree with other published information. Even for transmission-line application, where the number of operations would not be as many as for station use, this does not seem to be a reasonable life to use as a "basis of design".

It would also be very desirable to have published data in the form of curves on the volt-time breakdown characteristics of protector tubes. This is covered to a limited extent in figure 6 but is not complete enough to cover application in connection with switch-type insulators or bushings.

Several places in the paper mention is made of the discharge voltage of the tube whereas it is believed that "breakdown voltage" is intended. This is a minor point but may be confusing since in lightning-arrester work, the discharge voltage is usually considered as the *IR* drop after breakdown.

I. W. Gross (American Gas and Electric Service Corporation, New York, N. Y.): Knowing how a device is intended to function and the conditions under which it should be applied in practice are very helpful in studying the performance of the device itself when subject to operating conditions.

On the American Gas and Electric Company's interconnected 132-kv system, we have at the present time over 3,000 protector-tube assemblies installed on each phase conductor at each tower of six separate transmission lines varying in length from some 35 to 67 miles. Before these tubes were installed, staged field tests were made on tube designs to determine their suitability for interrupting power current. The initial tests made in 1932, were carried out on that part of the system where the maximum symmetrical rms short-circuit current was approximately 4,000 amperes. Further staged tests were made two years later on part of the system where the short-circuit current ran up to 10,000 amperes. It is interesting to note that when both of these tests were made, the problem of rate of voltage recovery rise of the system was not even considered. When these tests were made, the tubes were subjected to currents far exceeding the rated current which the design had predicted they were capable of interrupting. The point I wish to make here is that theoretical and design considerations must be co-ordinated with practical experience before the ultimate limits in performance of any protector device are known. From our experience in operating a large number of protector tubes in actual service during the past seven years, we have yet to find any indication that the tube has been subjected to power system current outside of its rating. The fact that our 132-kv system, being interconnected, far exceeds the 90-mile line length, indicated as a minimum by the authors in table II, indicates that we are not concerned with limits of line length in this particular application.

A considerable number of other installations on lower-voltage lines where protection has been undertaken on disconnecting switches, cables, and reactors, have operated satisfactorily from the point of view of tube rupture. On the basis of our experience with the application of protector tubes during the past seven years, we are wondering whether there is any evidence outside of theoretical considerations which indicates that the line length is such an important factor as the authors seem to stress in the paper. The problems which we have encountered in applying tubes may be summarized briefly as follows:

1. Ability of the tube to withstand weathering.

2. External tube flashover under lightning conditions. The record shows a decrease from approximately 11.4 per cent of flashed over tubes of the initial design to 1 to 1½ per cent on the newer designs. This problem seems to be reasonably under control.

3. As pointed out by the authors, the relay time setting must be sufficiently long to permit the tube to function without breaker operation. We have set a limit of about two cycles as a practical lower limit. Where high-speed breakers are installed to minimize conductor burning, line troubles, and for better system stability under fault conditions, the necessity of introducing longer relay times tends to undo the benefits possible with high-speed breaker action if this time delay is too great.

4. The disposal of ionized gases when the tube is operating appears to be a problem which should be given careful consideration particularly on tube application on the lower-voltage circuits where the conductor spacing is low. This consideration should be carefully watched, not only from the point of view of disposal of the gases from the tube vents but also from the viewpoint of possible traveling of the arc at the open gap end of the tube which may develop an arc on insulators or other closely adjacent equipment.

There is at the present time work being done in setting up a standard for protector tubes under the sponsorship of the lightning arrester subcommittee of the AIEE Protective Devices Committee. This work is now in second draft form, and this present paper, as well as the discussions which may be offered here, will be helpful in carrying on this work to a completion.

While it is not clear from the paper whether the authors are proposing that their table II be incorporated as a part of these standards now in progress, it is doubtful whether too much specific limitation should be placed on *tube standards* to the point where development in the device itself may be hampered.

F. E. Andrews and **H. A. Cornelius** (Public Service Company of Northern Illinois, Chicago): Although the probability of having sufficient lightning-stroke current to damage a protector tube is small, as indicated in the paper, such a failure occurred in the past lightning season on the Public Service Company of Northern Illinois 34.5-kv system. This 1,200 to 10,000-ampere tube had been in service just 14 days.

One disturbing point noted in the paper is the recommendation that where protector tubes are used, the high-speed-relay time should be at least two cycles. This is unpleasant news since it means adding external devices to decrease the effectiveness of such relays. If a tube should fail to clear after the relays have been slowed down, the fault might be on the system at least three cycles longer than at present.

Since the experience on which this recommendation is based is not given, an investigation was made of 34.5-kv lines on which protector tubes are installed in the instantaneous zone of the high-speed relays and of the line tripouts which occurred in the past lightning season.

The data are as follows:

Number of relay operations known to be due to tube operation 2

Number of relay operations probably due to tube operation 4

Number of known tube operations unaccompanied by relay operation 6

Included in the "relay operations probably due to tube operation" group are all otherwise unexplained line tripouts, so this figure may be high. Also, there is no practical way to determine the total number of tube operations. Therefore, the number shown as having occurred without causing relay operations is undoubtedly lower than it should be. Although these data are not conclusive, it indicates that using one-cycle relays has caused few unnecessary circuit outages.

The next point to be discussed is that accidental closing of the required external series gap has caused five tube flashovers with line interruptions resulting. The problem of holding the gap within the prescribed limits points to the need for further improvements. Is it practical to include the "series air gap" now used integral with the tube?

In regard to the protection provided, the statement is made that "where the protector tube gives protection to an insulator on a positive 1.5x40-microsecond wave at the critical flashover point, the protector will in general also protect for waves rising to flashover in shorter times or on negative polarity." The basis for including negative-polarity waves, which are about 15 per cent larger in magnitude than positive waves, within the protection provided by the tube, is not clear. The hyperbolic volt-time characteristic of insulation is apparently the basis for the protection provided by the tubes on steeper front waves than 1.5 microseconds.

Since successful operation and tube life vary with the degree of erosion of the tube walls and since the erosion to be expected at these widely separated tube installations would be greater than on lines having tubes on every pole, measurements of the erosion in 80 tubes were made. The data on the service life of these 80 tubes, erosion measured compared to years of service, etc., are given in table I of this discussion. Although the data are not very extensive, they are considered a representative sample for tubes in service for three years or less and indicate that severe tube erosion is rather uncommon.

One of the reasons given for the proposed standardization of protector tubes is that eight years of experience has been obtained with this device. Although in the past two years a much better understanding of protector-tube characteristics and of the effect of system characteristics on tube operation has been obtained, there still remains a question as to whether this device is ready for standardization. The basis for this questioning is the frequency with which troubles are encountered with this device. In support of the preceding statements, the experience with 196 three-phase sets of protector tubes, which have been installed at widely separated locations, in the past six years on the 1,100-mile 34.5-kv system of the Public Service Company of Northern Illinois may be cited.

1. Nineteen tubes failed apparently from the generation of excessive internal forces. Eight of these tubes were found destroyed after lightning storms and portions of the tubes were scattered 200 feet away. The other failures are not clear-cut as to cause, but it has been established that the failures were not due to erosion of the tube walls nor to having fault current flow less than the tube rating.

2. Practically all of these 19 tube failures have occurred in the past two years at seven different locations. Sixteen of the tubes have failed at four locations at various times. The number of tubes in service by ratings and the failures to date are as follows:

Tube Current Rating	Number in Service	Failures to Date
200–900	18	0
600–2,500	3	0
900–5,000	156	3
1,200–10,000	66	5
400–4,250	36	6
250–3,500	270	0
400–3,000	27	0
700–3,600	12	3
Unknown	2	2
	588	19

Another point of importance is the probable life to be expected of these proposed new standard tubes. Although the discussion on the basis of the design states that a 6,000-ampere tube is designed to withstand only one operation at maximum rated current when the current wave is completely offset, the discussion on the standard ratings of the tubes implies that more than one operation may be expected under service conditions. Unless the probabilities indicate considerably more than one successful tube operation in service, the new design does not appear practical. It is believed that effort should be made to provide tubes which will operate in service for a reasonable number of times. It is also believed that the tubes should be rated on the basis of expected field performance rather than on the basis of test performance. Such test performance appears widely divergent from typical operating conditions.

There are two points in connection with the proposed standard tube ratings: one has to do with a larger current rating than given in table II and the other with the reasons explaining why the physical length of the tube has been increased but the rating of the tube decreased.

1. At locations where 8,000 to 10,000 amperes short-circuit current may flow, none of the proposed standard tubes could be used, for the maximum current rating given is 6,000 amperes. The service experience at such high fault current locations where 1,200 to 10,000-ampere tubes have been in use for three to six years has been satisfactory. Pole-top switch insulator flashovers have been eliminated where tubes are installed, and there appears to be a general improvement in line performance. Unfortunately, the number of protector tubes in service by years is not available; but the average failure rate is estimated to be less than three per cent per year. In our opinion, the 10,000-ampere tube should be included in the proposed standard ratings.

2. Published data on the new standard protector tubes show them to be longer in the 34.5-kv class than before the change in rating by from one to four inches. This increased length should permit increasing the internal gap and thus the maximum 60-cycle voltage the new tube can clear after an operation, as well as the range of power current that can be interrupted at 60-cycle voltage. Instead, the new standard protector tubes are rated at approximately half the current interrupting capacity previously used. That is, on the old rating a 17-inch tube was rated 1,200 to 10,000 amperes, whereas on the new rating a 23-inch tube is rated 600 to 6,000 amperes. This seems to be a step in the wrong direction from the user's point of view, and the justification for such a marked change in tube rating is not apparent.

Two subjects considered of general interest are (1) some of the difficulties experienced while learning to install the tubes properly and (2) a description of two types of tube failure which have been observed.

1. Improper installation has caused trouble with about 25 tubes. The most common types of difficulty were due (*a*) to mounting the tubes on insulation having lower flashover values than the tubes, which accounts for about half the trouble experienced; (*b*) to flashover resulting from accidentally shortening the external gap; (*c*) to having the discharge gases directed so as to cause flashovers on adjacent equipment; and (*d*) to having insufficient clearance between the tube and the insulator it parallels.

2. The cases of tube failure due to power system current were generally characterized by an irregular parting of the tube fiber just above the metal base fitting which was attached to the mounting bracket. The bore of both the fiber and the base fittings had enlarged considerably. The erosion of the metal in many cases was approximately equal in amount to that of the fiber. One tube which had not failed was found with this same type of erosion, the bore having enlarged from $^{3}/_{4}$ inch to $^{13}/_{16}$ inch. This was located on a pole adjacent to one of the tubes which had failed and was thus presumably subjected to similar conditions.

On the other hand, in the case of the failure diagnosed as due to lightning stroke current, the tube was not appreciably eroded; and the fiber had parted at the metal base fitting with a relatively clean break.

While much of this discussion may seem to be devoted to tube shortcomings, we wish to point out that in over-all performance our use of tubes has been generally successful; and through their use, a definite reduction in certain types of lightning troubles has been accomplished.

C. Concordia (General Electric Company, Schenectady, N. Y.): From table II and the discussion under it, it might be inferred that protector tubes should be specified for proper operation on circuits having at least the required equivalent line length. However, I do not believe this is the authors' intention, or that such a specification is desirable. Instead, tubes should be specified for successful operation within their current rating and for recovery voltages no more severe than those listed in the table. That is, mere satisfaction of a certain system condition should never logically be taken as the fundamental requirement of any interrupting device; instead, it must be decided whether or not the permissible current ranges or recovery

Table I

Number of Lightning Seasons Tubes in Service		Erosion Measured		
Years in Service	Number of Tubes	$^{1}/_{16}$ Inch	$^{1}/_{32}$ Inch	0 Inch
3	30	2		28
2	41	3	7	31
1	9	1		8
	80	5	8	67*

* Twenty-one of these tubes showed arc scars, etc., indicating that operation had occurred. The remaining 46 tubes probably had not operated.

voltages are exceeded, the line length serving as a guide to this decision. Thus, the information given in this table should be of considerable assistance in assuring proper application of tubes.

A. C. Gohlke (Cleveland Electric Illuminating Company, Cleveland, Ohio): This paper gives a clear outline of the many variables to be considered in the application of protector tubes to a given power line and the standardization of protector-tube designs would facilitate the correct tube applications to a great degree.

Our experience with protector tubes of the 34.5-kv class has indicated the following:

1. Tube failures from excessive impulse discharge currents have been most common. Shattered tubes have been found in the 5,000-ampere class as well as the 1,500-ampere class.

2. External flashover of tubes has occurred in a number of instances, indicating high impulse discharge currents or insufficient margin of external insulation over internal-gap breakdown.

3. Several cases of insulation failure of tube walls have occurred showing path of dynamic current from internal electrode through wall of tube to external ground.

4. Tubes have continued to clear successfully after repeated operations at locations of approximate minimum current values.

5. External finishes on tube walls have not been effective for more than three to five years.

R. J. Patterson, R. R. Schump (nonmember), and **E. H. Grosser** (nonmember; all of Commonwealth Edison Company, Chicago, Ill.): It seems to us that, with one or two exceptions, the paper covers the subject very thoroughly. Our only difficulty was in co-ordinating the various factors dealing with protector tubes, and we are of the opinion that a more straightforward presentation would help when and if this information is written into standards.

Enlarging on this matter, it would appear preferable to separate design factors from such application factors as system characteristics, lightning severity, anticipated life, and installation and maintenance methods. Incidentally, we should like to see someone from either of the manufacturing companies present a discussion of this paper giving up-to-date information on electrical connections, various methods of installing protector tubes on lines of various types, relative protection to be expected with different arrangements and numbers of tubes per phase per mile, and methods of mounting the devices on structures. We should also be interested in a discussion of the limitations of these devices in protecting inductive and possibly capacitive apparatus, which was not covered in the paper.

A few specific comments on the paper are given below:

1. In tables I and II, it is not clear that the circuit voltage rating is also the voltage rating of the protector tube. Also, it is difficult to tell whether the columns 2 and 3 values for discharge critical voltage do or do not include the recommended series gap. If they do, then the voltages corresponding to the protected arcing distances shown are more than ten per cent greater than the tube discharge voltage as stated in the second paragraph under "Protector-Tube Characteristics." We wondered if tolerances for erratic discharge voltages were also added to the tube discharge voltages shown. Along this same line, it would be interesting to know whether the series capacitances of the tube and external gap are such as to prevent a cascading type of discharge, in which either the tube or gap operates first. If this did occur, the voltage existing across the combination would probably be limited to the discharge voltage of the tube alone.

2. Under item (*e*) of the section on "Protector-Tube Characteristics" it would be of interest to learn to what extent the impulse and power-frequency characteristics of tube and external gap are affected by rain, humidity, and dirt.

3. Does figure 7 apply to all ratings of protector tubes?

It may be of interest to learn of our experience with the revised installation of protector tubes on a 33-kv wood-pole line. This line, which is about three miles long, has two conductors spaced nine feet on a wood crossarm and the third conductor mounted on the ridge pin, five feet nine inches above the plane of the other two conductors. The first two years of operation, with no protector tubes installed, was unsatisfactory, three cases of lightning trouble occurring in 1936 and eight in 1937. Then protector tubes were installed on all three phases of the line, but spaced about ten spans apart. Seven cases of lightning trouble occurred with this arrangement in 1938. As a result of this operating experience, it was decided to modify the protective installation to provide one protector tube on the top conductor only on every pole throughout the line, except that three gaps were installed on corner poles and such few poles as have flat configuration. Ground resistances were reduced to a value which calculations indicated would prevent flashover voltage between phase wires being attained with severe stroke currents. With this protective scheme in operation during the entire 1939 lightning season (which, however, has not been an unusually severe one), no lightning troubles or outages have occurred on this line to date. Although the minimum and maximum ratings of the tubes were raised for a portion of the line, the improved performance is attributed to the manner of locating the gaps on the poles.

Our comments on the standardization portion of the paper are as follows:

The proposed standard line of tubes as given in table II, taking into consideration the application of a standard tube at reduced voltages, should suitably cover requirements of various systems. The basis of design, namely, one, two, or three operations at maximum rated current with completely offset wave for the 1,500, 3,000, and 5,000 to 6,000-ampere tube, respectively, seems to give little assurance of realizing a fair amount of protection for the investment in tubes and their grounds. The tentative selection of 1,500, 3,000, and 5,000 to 6,000 amperes for maximum rating indicates that some overlapping of currents is permissible for successful operation; otherwise a larger number of tubes should be required to adequately cover line conditions. If this is true then it would seem that a 3,000-ampere tube, for instance, could be expected successfully to withstand more than two discharges at 3,000 amperes with completely offset wave.

It would seem desirable to incorporate in the paper some indication of the number of operations which can be expected from a tube for the most severe, average, and least severe conditions assuming the tube grounding resistance to be zero.

Some mention might also be made of standardization of mountings so that a tube of one manufacturer could be replaced, if desirable, with a tube of another manufacturer without replacing the bracket.

As the tube rating is appreciably affected by the bore diameter, it would be desirable from the user's standpoint to have the nominal diameter stamped on the name plate. This would assist in determining when a tube should be replaced. Also, the construction should be such that the bore can be readily determined by measurement in the field.

A. D. Forbes (Westinghouse Electric and Manufacturing Company, Sharon, Pa.): This paper has been limited by its authors to the field of the type of protector tube which is used for the protection of transmission-line insulation. There is also the type of deion protector usually referred to as a "deion gap" which, to date, has been used principally for the protection of distribution-transformer windings. It may be well to point out the similarities and differences of this type of equipment.

The deion gap operates on the same principle as the protector tube—deionization of the power arc by means of gas generated by decomposition of fiber by the arc.

The deion gap differs from the protector tube in two respects, however. First, the deionizing section of the deion gap consists of a number of parallel slots instead of a cylindrical hole as used in the protector tube. The slotted construction allows the two opposite walls to be close enough together that there is no minimum power current which the deion gap will interrupt—it will clear from zero amperes upward.

Second, series resistors are normally used with deion gaps. The series resistor limits the power follow current regardless of the short-circuit current of the system. There is therefore no maximum current which can be interrupted and the deion gap can be applied universally to any power system.

Data which have been presented by Hodnette,[1] Ludwig,[1] Bellaschi,[2] Sporn,[6] and Gross[8] indicate that the probability of a 50,000-ampere surge each year is 0.23 per cent to 3.7 per cent. More recent experience with deion gaps in transformers on distribution circuits indicates a probability of about 0.9 per cent for 50,000 amperes, and 0.1 per cent for 100,000 amperes. Experience gained indicates that gaps for transformer application which can successfully discharge a surge of 100,000 amperes decreasing to half value in 50 microseconds are satisfactory. We note that the surge-current capacity of the protector tube, as mentioned under "Protector-Tube Characteristics" is 50,000 to 100,000 amperes for a duration of 20 microseconds to half value. For applications where protector tubes are used, there are possibly more parallel paths for lightning to drain off to ground and possibly because of this, the high surge-current capacity of the deion gap, for transformer application, is not required by the protector tube for line application.

REFERENCES

1. SURGE PROTECTION OF DISTRIBUTION SYSTEMS, J. K. Hodnette and L. R. Ludwig. ELECTRICAL ENGINEERING (AIEE TRANSACTIONS), June 1937, page 683.

2. Lightning Currents in Field and Laboratory, P. L. Bellaschi. Electrical Engineering (AIEE Transactions), August 1935, page 837.

3. Lightning Currents in 132-Kv Lines, Philip Sporn and I. W. Gross. Electrical Engineering (AIEE Transactions), February 1937, page 245.

H. A. Peterson, W. J. Rudge, A. C. Monteith, and L. R. Ludwig: The discussions presented on this paper are very encouraging to the authors as they not only bring out factors that were not included in the paper but also give very valuable operating experience on the device under discussion.

Referring to the discussion by Mr. Westrate, the authors wish to point out that the demonstration tests proposed cover extreme conditions which are very unlikely to exist in the actual application of tubes to power systems. In the first place, in actual operation numerous factors affect the magnitude of the short-circuit current which will be passed through the tubes; that is, the point on the wave at which lightning strikes, the offset factor in the first cycle of current flow, the reactance of the lines, etc., will usually result in a peak current through the tube which is lower than the maximum current called for in the test. The resultant effect is in the direction to give less erosion, or in other words a greater number of operations.

In the second place, it should be recognized that usually it is the minimum current which dictates whether or not the tubes will clear. It is very likely that in actual practice the minimum current of the system will be above the minimum rating of the tube, and the system recovery voltage will generally be less severe. As the result of this influence the tubes are capable of a greater number of operations before the tube bore erodes to the point where the tubes will fail to clear properly. There have been many cases pointed out in the literature and in the discussions presented before the AIEE where tubes have operated numerous times without reaching the end of their useful life. It is our feeling that the proposed test can be used only in a comparative sense. The actual number of operations can be determined only from experience with the tubes in the field.

We are in agreement with the thought expressed that the protector tube can serve as a secondary protection device. It will serve to protect line insulators, disconnecting switches, and the like. However, we wish again to call attention to the fact that we would expect tubes used in this fashion to have a shorter life from the standpoint of erosion than tubes used to protect every structure along the transmission line. This would be particularly true in cases where the protector tube is attached to a station which is fed by a highly insulated line, as practically all strokes in the vicinity of the station will cause operation of the tube, if the oil circuit breaker or pole-top switch were in the open position. Naturally, tubes used for this purpose would have to be replaced more frequently than in cases of normal application. It is entirely possible that additional tubes for, say the first two or three structures out from the station, would divide the number of operations in such a way as to prolong the periods required between tube inspections.

Some of the principles used in this device are incorporated in a tube for the protection of all apparatus in the voltage classes 15 kv and below. There are features included in these tubes, however, that are not incorporated in the tubes discussed in this paper and their standardization should be considered separately. We were particularly interested in the comments on the application to free-neutral systems. It will be of interest to again review this experience in the course of two or three years. It is quite possible that too conservative a point of view is being taken in regard to the application to free-neutral systems.

The volt-time curves Mr. Westrate refers to are available in published literature of both manufacturers. In making use of them, one point should not be overlooked. The laboratories of the manufacturers are able to check each other with a very close degree of accuracy on $1^1/_2$x40-microsecond critical flashover tests. However, there are discrepancies between laboratories on values obtained for breakdowns at short times in the region of one-half microsecond. Therefore, in making an application, volt-time data for protector tubes obtained in one laboratory should be compared with volt-time data for insulators obtained in the same laboratory.

Mr. Westrate questions our use of the term "discharge voltage", stating that he believes breakdown voltage is intended. We agree that there is need of clarifying both the terms and their definitions. We feel that this can best be done by the AIEE committees who are at present writing standards for the tubes, and we are referring this matter to the proper committees.

Mr. Gross points out that miles of line are not of particular concern to him in the application of tubes, since their minimum miles of line far exceed the 90-mile minimum required in the paper for 138-kv tubes. This is undoubtedly true while the system is interconnected. However, there may be operating conditions in which a portion of the 138-kv system is disconnected and this portion may have less than the 90 miles required in which case the recovery voltage will be more severe with corresponding risk of tube failure. Such conditions probably correspond to emergency conditions and not conditions that will normally exist on the 138-kv system. This is just another way of saying that tubes will be capable of a larger number of operations under usual service conditions as pointed out before.

It is true that in the case of the system cited by Mr. Gross miles of line or the corresponding recovery voltages are not major factors. However, there have been numerous other cases in which the length of line or severity of the recovery voltages have been of major importance in the application of tubes.

In connection with the question of how important length of line is in determining the recovery characteristics, tests have been made not only on the miniature transient analyzers referred to in the paper, but in the field as well. These tests show definitely that the recovery characteristics are affected by miles of line. It should be thoroughly appreciated, however, that the miles of line given in table II are purely to serve as a guide for application and it was not the intent to use miles of line to specify tube characteristics. This also applies to Mr. Concordia's discussion. The tube characteristics should be stated in terms of the recovery voltage characteristic for which they are designed, and it was our intent to do this in specifying these characteristics in the paper.

We agree with the thought suggested by several discussers that the slowing up of high-speed relays introduces another complication, and from this point of view, an unfortunate one. However, a line properly equipped with tubes should normally not require the operation of the relays. This represents a definite improvement in performance both from the standpoint of increased stability and from the standpoint of a decreased amount of conductor burning. In the possible event of a tube failure to operate, or in cases where insulator flashover cannot be controlled by the tube, such as might occur with an accumulation of dirt or the like on the insulators, the two cycles, in general, will not appreciably change the amount of burning nor affect the stability.

The operating experience outlined by Mr. Gohlke is of interest in connection with the performance of the device under discussion. We believe, however, that the tubes in question are of special design to meet special system conditions, and not tubes designed for general application such as are being considered in this paper.

In answer to the discussion by Messrs. Patterson, Schump, and Grosser, it should be pointed out that the factors affecting the different distributions of protector tubes along the line have been analyzed and presented in the literature. We refer to "Protection of Transmission Lines Against Lightning—Theory and Calculations" by L. V. Bewley, *General Electric Review*, June 1937.

With regard to the question of electrical connections and methods of mounting, we believe that both manufacturers' bulletins show typical mounting arrangements and methods of connections and by referring to these publications, this information can be obtained.

With regard to the question of protecting inductive and capacitive apparatus, the question is not clear to us as to just what was intended. However, we believe that our comments on Mr. Westrate's discussion answer this point.

With regard to item 1, the voltage rating contained in table I and table II is the tube circuit-voltage rating. The nominal voltage rating of the tube is the maximum permissible continuous rms voltage across the tube assembly, including the series gap, and is at least the circuit voltage divided by the $\sqrt{3}$. The impulse values given in table I include the listed series gaps appearing also in table I.

With regard to item 2, the extent to which the breakdown characteristics are affected by rain can be determined for standard rates of precipitation, but there appears no practical way of determining the effect of humidity and dirt, as these factors will vary so widely with different localities that it seems impractical to evaluate them.

With regard to item 3, figure 7 of the paper is typical of the characteristics of all protector tubes, although the specific values given apply only to one particular tube, and one particular voltage rating. This curve was included to show how, in general, the recovery characteristics of the tubes

Modernization of a Transit System—Factors That Determine the Choice of Vehicle

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THE transit industry is facing serious economic problems. Shrinking revenues, due largely to the competition of the private automobile, and increased operating expenses have together so decreased the margin between income and expenses that many systems are now in financial straits. The best solution for these problems, so far advanced, is to modernize the equipment and rehabilitate the service. Some lines have already been modernized; most of the remainder badly need modernization. Present equipment is old and expensive to operate; the service is slow, infrequent, and generally unattractive to the riding public. Through substituting new, fast, comfortable vehicles, run on frequent headways, for the present obsolete equipment and through aggressive management, most transit systems, if not all, may regain a considerable portion of their lost traffic and thus get back to a more satisfactory financial condition.

Most city transportation systems were originally equipped with street cars, because at that time the street car was the only transit vehicle known. At present, in a well-planned modernization program, two additional vehicles, the trackless trolley, or trolley bus, and the gas bus, merit consideration.

Even engineers and operating men disagree as to the relative merits of the three types of vehicles. There are "street-car enthusiasts" and "bus enthusiasts", while still others believe that all three may have a legitimate place in a modern transportation system. In view of the large expenditures involved in even a very modest modernization program, these differences of opinion make appropriate at this time some explanation of the basic factors governing the choice of vehicle, a selection that should be based, as far as possible, on facts rather than on personal preference for a particular type of conveyance.

The purpose of this study is twofold: first to show the application of the engineering method to the problem of selecting the most suitable vehicle with which to modernize an existing transit line; and second, to determine as nearly as possible, for average conditions, the range of traffic volume within which each vehicle is most economical.

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Requisites of a Modern Transportation System

A modern transportation system should fulfill three fundamental requirements. These are: first, it should render adequate service; second, the vehicle used should be attractive to its patrons; and third, the over-all cost of operation should be the least practicable in order to make a low rate of fare possible. The three types of vehicles will next be compared with respect to those qualities most essential to a modern transportation system.

First, Adequate Service

The principal factors that determine the adequacy of service, from the patrons viewpoint, are safety, frequency of service, accessibility, and speed. Of these the first is the most important.

Safety. Because the street car follows a pair of rails, in case of icy streets, foggy weather, or other unusual conditions, it may be expected to follow a definite fixed route. Rubber-tired vehicles must be steered, and hence under such unusual conditions are at some disadvantage. However, experience has shown that, given proper operating methods, such as the use of chains, and the sanding of slippery streets, these hazards can be reduced to a minimum.

With street cars, passengers must board or alight from the cars in the middle of the street, but with the rubber-tired vehicles loading takes place at the curb. Curb loading has the advantage that it is less dangerous for the patron because he is not forced to pass through vehicular traffic in order to reach the public conveyance.

Frequency of Service. In the eyes of the public, frequency of service probably has a greater bearing on the quality of a transportation service than any other

would vary as a function of the current passed through the tube.

With regard to the question of standardization of mounting fitting, also of stamping the tube's original diameter on the name plate, we are referring these matters to the proper committees.

Messrs. Andrews and Cornelius bring out a point that is too often overlooked. The length of series gap given in the paper is based on obtaining the performance given in the tabulations. If the insulation of the systems is high then the series gap can be increased minimizing the necessity of careful setting of the series gap. These gentlemen have also given very valuable operating data which will be of interest to the art as these data show that in actual practice more operations can be obtained than outlined for the demonstration test.

We have noted with particular interest the operating experience of tubes reported by Messrs. Andrews and Cornelius. However, we wish to caution against comparing these data with the data presented by Messrs. Gross and Sporn, for it is our understanding that in most of Mr. Cornelius' and Mr. Andrews' cases, tubes have been installed on pole-top switches and isolated structures, whereas the figures given by Messrs. Gross and Sporn are for cases where tubes were installed on every structure along the entire length of line. As pointed out in answering Mr. Westrate, tubes located at terminal structures or guyed structures and located intermittently along the line, will be subjected to a greater number of operations than tubes located on each structure along the line, and for this reason will have a shorter life.

The authors feel that it is very desirable to have a standardization at the present time as this allows starting with a common basis. This will provide a method of making a comparison of the performance of devices for any system. We should not, however, lose sight of the fact that if the basis selected for standardization at the present time is not correct then it certainly can be changed when this fact is established. It should be recognized that the physical length of the protector tube does not determine the rating. Rather, this is dependent on the actual space between internal electrodes, bore, and wall strength. Too much stress should therefore not be placed on the physical dimensions of tubes having different current ratings but the same voltage rating. It should be expected as a result of this standardization that more uniform tube designs will result with a greater reliability of operation.

single factor. The modern automobile has taught the public to expect from its transportation system accommodation in a measure approximating in convenience the house-to-house service of the automobile. Unfortunately cost is a limiting factor. The best that can be done is to render as frequent service as possible, with the smallest vehicle practicable to operate within the economic limitations.

Accessibility. Of almost equal importance with frequency of service is accessibility. Formerly the common practice was to space transit lines almost a mile apart. The patron walked, not from choice but of necessity, the half mile to the car line. With the advent of the automobile, an increasing percentage of the population refuses to walk this distance. Experience has shown that where the walking distance is much over a quarter of a mile, or where the service is too infrequent, the public will begin to use other forms of transportation.

This situation may be handled in three ways. One is to space the lines more closely together. This method has the disadvantage that unless the population is very dense, the traffic on all lines will be so light that it is economically impossible to give frequent service on any of them, even with small vehicles. A further disadvantage of this method is that the large number of small vehicles that would be required leads to congestion in the metropolitan areas. However, this may not be as great a limitation as might at first be supposed. The private automobile now on the street carries on the average approximately $1^3/_4$ persons per car. If the use of small vehicles on closely spaced lines would attract back to the public transportation system any considerable number of people that would otherwise use their own cars, the results might well be a decrease in traffic congestion.

The second possibility is to use small vehicles, usually busses, as feeders, transferring the passengers to a few trunk routes, on which the traffic will be heavy enough to warrant frequent service with larger and more economical units. The disadvantage of this plan is that a large proportion of the passengers must transfer.

A third method is to use a terminal system,[1] as that proposed by A. V. Eastman, in which all lines from the outlying districts terminate in two or more terminals located near, but still outside, the metropolitan area. Heavy trunk-line service is provided between these terminals, over several alternate routes so spaced as adequately to cover the metropolitan district.

Speed. Much of the appeal of the private automobile, aside from its convenience, is due to its superior speed. Although speed is important in a transit vehicle, it must not be attained at a sacrifice of safety. Owing to the large number of stops which it must make, no public conveyance in use on city streets will ever be able to equal the speed of the private automobile. A high schedule-speed (by schedule-speed is meant the average speed including all stops, layovers, etc.) is desirable for two reasons; first, it speeds the passenger to his destination, and second, it reduces the cost of giving service. Costs are reduced because both the number of cars required to run a given service and the amount of platform labor are decreased.

The schedule-speed of modern transit vehicles is much superior to that of their predecessors. For example, the Presidents Conference Committee car, usually called the PCC car, is designed to have a schedule-speed, on level track, of 14 miles per hour with eight seven-second stops per mile. The trackless trolley as far as acceleration, etc., are concerned is equally good. The gas bus, because of its limited power supply, and, if it is of the mechanical type, the necessity for shifting gears, is definitely slower than either of the other two; particularly if the number of stops per mile is large. This is one of the factors that makes the gas bus better suited to lines of light traffic, where the number of stops will be low.

The gas bus has a considerable advantage over both the other vehicles, in that, because it does have its own power plant, its route is not restricted to that of an overhead trolley. In times of emergency or even under normal[2] conditions this may be a very valuable asset. The self-contained power plant also makes possible both local and limited or express service on the same street without additional complications or investment. This double service is also made possible with the trackless trolley by use of either an auxiliary turnout in the overhead at the overtaking point, or of double overhead; either equipment requiring some additional investment. With street cars it is not feasible to operate both local and express service on the same street.

Second, Attractive Properties of Vehicle

The private automobile has made the public more critical than formerly of its transit vehicles. In order to attract patronage the vehicle used should be comfortable to ride in and reasonably quiet in operation, and should be convenient to board and alight from.

Comfort and Quiet. In all of the new vehicles, regardless of type, much more attention is now being given to comfort and quiet. Seats are upholstered, and by an ingenious use of rubber in both running gears and body, the noise has been greatly reduced and the riding comfort improved.

Convenience. Because of curb loading, in convenience of ingress and egress, the advantage is very much in favor of the rubber-tired vehicles. The principal disadvantage of curb loading is that it may necessitate establishment of loading zones at the more important points, especially in business areas. To be effective, these zones must be kept clear of parked automobiles, so that the transit vehicle may draw in to the curb to pick up or discharge passengers.

Third, Cost

In general, operating costs vary with both the size and kind of vehicle. For a given type, the operating cost per vehicle mile is less for a small conveyance than for a large one, but the cost per passenger mile is just the reverse. For a unit of given size, the gas bus requires the smallest capital investment, but has the highest operating cost (exclusive of interest and depreciation) of the three. Consequently it is best suited to lines of light traffic where the higher operating cost per mile is more than compensated for by the lower fixed charges on the smaller investment required. Hence, at light traffic volumes it yields a larger net return, with better headways and a smaller capital investment than would be possible with either the trackless trolley or the street car. The street car is best suited to very heavy mass transportation, where the traffic is heavy enough to require a large unit and is able to support the charges on the extra investment in track. Hence, with very heavy traffic, the street car, because of its larger size and lower operating cost per passenger mile, yields a greater net return, with entirely acceptable headways, than would be possible with either the trackless trolley or the gas bus, and this in spite of the large investment required for the track. The trackless trolley is intermediate between the other two, both in operating cost and investment.

As in any other business, in order for a transit system to continue as a going concern, its income must exceed, by a reasonable margin, its expenditures. Un-

1. For all numbered references, see list at end of paper.

fortunately, this has not been the case in the transit industry, as a whole, for many years.

Two methods for remedying this deficiency have been tried. The first is to increase the income by increasing the rate of fare; the second is to raise the net income by improving the service so as to attract more patronage, at the same time reducing the cost of operation per passenger.

The efforts to increase the income by increasing the rate of fare have not been uniformly successful; in fact, in some cases where fares have been increased the resulting decrease in traffic has very largely offset the effect of the fare increase.

The second method, that of increasing the net return by improving the service, is much to be preferred. The most effective way of improving the service, and at the same time holding down costs, is to modernize the system by replacing old equipment with new vehicles properly chosen to fit the traffic conditions of each individual line.

So far as the author is aware, in all cases where a well-planned modernization program has been put into effect, the results have been better than were anticipated.[3-6] In addition to operating at reduced cost, the new vehicles have won and held increases in traffic that in many instances were truly remarkable.[2,7-10]

Factors That Determine the Choice of Vehicle

The foregoing discussion indicates that many factors influence the choice of vehicle in a given case. These may be classified roughly into two groups; first, those that have to do with the psychological appeal of the vehicle and, second, the economic factors.

The psychological or human elements of the problem are quite difficult or impossible to determine quantitatively and their relative importance in a given case is largely a matter of opinion or personal preference. For this reason no attempt has been made to determine which vehicle will have the greatest popular appeal but rather attention has been confined to the purely economic elements involved. Therefore, in what follows it is assumed that for equal headways the different vehicles are all equally capable of attracting patrons.

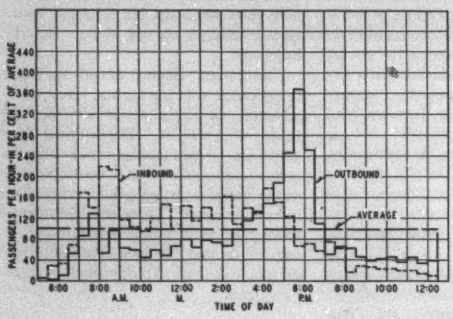


Figure 1. Typical curve of passengers per hour as a function of the time of day

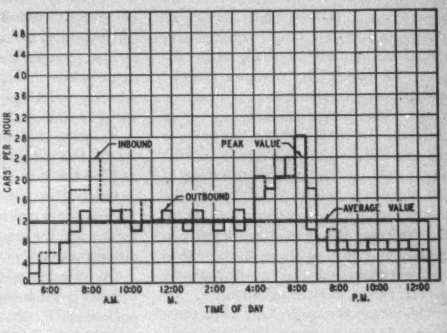


Figure 2. Typical daily car-demand curves

Economic Considerations

In determining the best vehicle with which to modernize a given line, three factors are of primary importance. These are, first, the net return; that is, the excess of income over total operating expenses; second, the possible headways; and third, the investment required.

The first is important because it determines the most economical vehicle to use. The second is important because it fixes the frequency of service and therefore, from the patron's viewpoint, largely the quality of the service rendered. The third is important because it determines the amount of new capital that must be provided.

For each kind and size of vehicle the net return, the headway, and the required investment all vary with the traffic to be handled. In a given case, the vehicle selected will normally be the one that can be operated most economically for the traffic existing. There are, however, exceptions to this rule. Sometimes, particularly with lines of light traffic, the most economical vehicle would require headways too large to give reasonably good service. In that case a smaller vehicle, operated with shorter headways, is desirable even at some sacrifice in the net return. Other exceptions may be found. For instance, the need to limit the number of types and sizes of vehicles on the system may result in choice of a vehicle other than the one that will give the best economy.

The reader has probably surmised that the problem of selecting the proper vehicle involves individual study of each line. This is the case particularly if an accurate forecast of the probable net return with the new equipment is to be obtained. However, as was noted previously, each vehicle has a certain volume range of traffic over which it is most economical. If this is known beforehand, then the problem of selection is greatly simplified.

Basic Data. Before the most economical traffic density range is determined for each type of vehicle the basic data must be established on which the solution of the problem depends.

The following general data were assumed to apply to all vehicles alike (the basis for each assumption is discussed in greater detail below): average schedule speed, 13 miles per hour; interest rate, five per cent; average fare, six cents; and duration of service, 19½ hours per day. Additional data applicable to specific vehicles are given in table I.

These data were derived from various sources. The average schedule speed of 13 miles per hour was estimated. As was mentioned before, the PCC car is designed to have a schedule speed of 14 miles per hour, with eight seven-second stops per

mile. The trackless trolley is equally fast and modern busses could probably do as well in any service in which they would likely be used.

This value is probably high for dense traffic but it should approximate average conditions fairly closely. Admittedly, schedule speeds vary on different lines, but in general on a given line the schedule speed will be very nearly the same regardless of vehicle type.

The interest rate is taken at five per cent, as being approximately average. A low rate would be more favorable to those vehicles that require large capital investments.

The average fare of six cents is probably too low for the country as a whole. Its value would not affect the region of best economy in any case, although it would have a very decided effect on the net return. Consequently the comparison, as between vehicles, is the same regardless of the fare. The value of six cents was assumed because it is almost exactly the average fare, including transfers, etc., for the Seattle Municipal Railway System.

An allowance of ten per cent of the vehicles required on the peak was made for spares. This favors the gas busses slightly for, generallyspeaking, the availability of the electric vehicles is better than that of gas units.

The data listed in table I were also drawn from several sources. The values for vehicle-unit costs (column 2 of table I) were taken in part from manufacturers' bid prices, in part from published prices, or were estimated in those cases where information was not available from either. To determine accurate unit-cost data for the gas busses is particularly difficult because of the wide variations in specifications and manufacture for busses nominally of the same passenger capacity.

Depreciation. The life of new street cars is taken as 20 years; that of the trackless trolley as 10 years. These assumptions are close to the usual practice with regard to these vehicles. Except where stated otherwise, the useful life for the 30- and 40-passenger gas busses is taken as $6^2/_3$ years. For the 22-passenger gas bus, because of its generally cheaper construction, a useful life of 3 years is assumed. Practice with regard to depreciating gas busses varies considerably with different operating companies, the useful life assumed generally varying between 5 and 10 years.

As a matter of fact, any of these vehicles can be maintained almost indefinitely. Some street cars, still in operation, are more than 35 years old; similarly, trackless trolleys will last more than 10 years, and gas busses more than $6^2/_3$ years. In fact, the average age of the gas busses now in use in this country is estimated to be over 10 years. But few people nowadays want to keep a street car 35 years. Neither will they want to keep a trackless trolley or a gas bus more than a reasonable length of time. From a practical standpoint, if a vehicle is kept in service too long, operating costs go up, and generally patronage goes down. Modern advertising has taught the public to expect new models in its transit vehicles as well as in its private automobiles.

The assumed life of $6^2/_3$ years is undoubtedly very conservative for busses of good manufacture. Of course, if the depreciation rate were reduced these vehicles would make a somewhat better showing. Similarly, if the depreciation rate for the street cars were increased it would suffer by comparison. The effect of changing the depreciation rate is shown more in detail, for the case of the 22-passenger gas bus, in figures 20 and 21.

Use of a vehicle having a shorter life is not without advantage. For example, suppose that the condition of traffic and track on a given street-car line were such that the line could be modernized at practically equal cost with either new street cars or gas busses. Equal cost means that if new street cars are used they must be kept in service for 20 years in order to recover the investment. If on the other hand, the line be modernized by using, say, 40-passenger gas busses, which are "written off" the books in $6^2/_3$ years, the line could have new equipment of the same or better type, should better-type equipment be then available, every $6^2/_3$ years. Or if at the end of the depreciation period the equipment had some useful life remaining it could be kept in service until completely worn out. Each time new equipment is put into service the result will normally be an increase in traffic, for which the type of vehicle should have credit.

Another disadvantage of a long-term program is that frequently community development makes necessary improvements, such as grade changes, repairing operations, etc., which were not taken into account in the original calculations.

The depreciation rate on the new investment in track, which is assumed also to include any necessary rehabilitation of the overhead, has been taken at four per cent. The assumption is that street-car operation will be continued indefinitely. If street-car operation is to be discontinued at the end of the usual life (20 years) of the new rolling stock, the depreciation rate on the new investment in track will properly be five instead of four per cent. The depreciation rate on the overhead for the trackless trolley has been assumed to be five per cent. The above procedure is more than fair to the street car.

No attempt has been made to depreciate the old investment in track or overhead on the ground that if present street cars are to be replaced, for example by gas busses, all the present investment in track will have to be retired. Salvage value is ignored in all cases. Also no allowance is made for removing the old rails from the street in case rail operation is abandoned. Probably the most satisfactory method of handling this problem is to cover the old rails with asphalt until repaving becomes necessary, at which time they can be removed inexpensively.

Operating Costs. The operating costs per vehicle mile given in table I are estimates. Some of the values check reasonably well with recently published data[11] for similar vehicles. In different

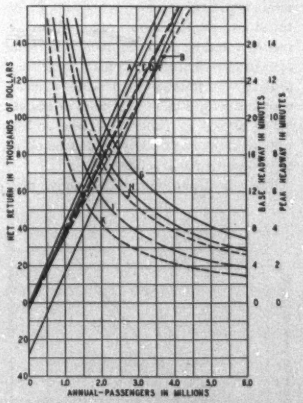


Figure 3. Net return and headway versus annual passengers, three-mile line, L = 0.9, m = 2

A—Net return, PCC car, with no track rehabilitation cost
B—Net return, PCC car, with track at $100,000 per double-track mile
C—Net return, 44-passenger trackless trolley
D—Net return, 30-passenger trackless trolley
E—Net return, 40-passenger gas bus
F—Net return, 22-passenger gas bus
G—Headway, PCC car
H—Headway, 44-passenger trackless trolley
I—Headway, 30-passenger trackless trolley
J—Headway, 40-passenger gas bus
K—Headway, 22-passenger gas bus

parts of the country operating costs vary considerably, owing primarily to differences in wages, and in fuel and power costs. The values quoted are as nearly average as could be determined from the data available. In sections where electric energy is expensive, the operating costs for the electric vehicles will be more than the figures quoted in table I, while cheap gasoline will tend to lower those for the gas busses.

Another cost, difficult to determine in a general study of this kind, is taxes. The difficulty arises from the fact that there are almost as many and varied methods of assessing taxes against transit systems as there are transit systems. In a specific case the taxes will be known and can be taken into account. The fact that taxes are herein neglected will not, in general, greatly alter the region of best economy for the various vehicles, because taxes would affect all to almost the same degree.

Determination of the Most Economical Traffic-Volume Range for Each Vehicle. From the basic data, previously established, values of annual-passengers, annual-vehicle miles, annual-revenue, annual-operating cost (exclusive of interest and depreciation), required investment, interest, and depreciation, total operating cost, and net return, were computed for various assumed values of headway and length of line for each of the vehicles shown in table I. These values were so chosen as to cover the usual range to be met with in practice.

The quantities enumerated above may

Table I

Type of Vehicle	Unit Cost of Vehicle (Dollars)	Vehicle Seating Capacity	Depreciation (Per Cent)			*Average Operating Cost (Cents Per Mile)
			Vehicles	Track	Overhead	
54-passenger PCC car	15,000	54	5	4	4	23.0
44-passenger trackless trolley	13,000	44	10	None	5	18.5
30-passenger trackless trolley	9,500	30	10	None	5	15.5
40-passenger gas bus	10,000	40	15	None	None	21.0
22-passenger gas bus	2,200	22	33⅓	None	None	14.25

* Excluding interest and depreciation.

be calculated individually; or, more conveniently, particularly if only the net return is required, the various relationships can be put into a single equation, thus:

$$R = AF - 365k_1l_0C_a - \frac{k_2PUlC_p}{V} - \frac{k_4T}{2} \quad (1)$$

or

$$R = \frac{alF}{2} - 365k_1l_0C_a - \frac{k_2PUlC_p}{V} - \frac{k_4T}{2} \quad (2)$$

or again

$$R = 730LFSl_0C_a - 365k_1l_0C_a - \frac{k_2PUlmC_a}{V} - \frac{k_4T}{2} \quad (3)$$

where

R = net return
P = 1.1 = ratio of total vehicles, including spares to the vehicle required on the peak
F = average fare in dollars = 0.06
l_0 = hours of service per day = 19.5
V = schedule speed = 13 miles per hour
U = unit cost of vehicle in dollars
k_1 = average operating cost per vehicle-mile in dollars, exclusive of interest and depreciation
k_2 = interest rate plus depreciation rate (in decimal) on vehicles
k_4 = interest rate plus depreciation rate (in decimal) on track and overhead (street car) or on overhead (trackless trolley)
h = headway in minutes
C_p = cars per hour during peak period
C_a = average cars per hour = average ordinate of car-demand curve
T = cost of rehabilitating track and overhead, for the street car, or cost of overhead for the trackless trolley, in dollars per double track mile (DTM)
S = seating capacity of vehicle
L = average loading of vehicle, that is, the ratio of the average number of passengers per trip to the vehicle seating capacity, in decimals
l = round-trip length of line in miles
A = total annual passengers
a = total annual passengers per route mile = $2A/l$
m = ratio (in decimal) of the cars per hour on the peak (C_p) to the average, or base, cars per hour (C_a); is also equal to the ratio of the average, or base, headway to the peak headway

The first term, AF, is the annual gross income; the second term, $365k_1l_0C_a$, is the yearly operating cost exclusive of

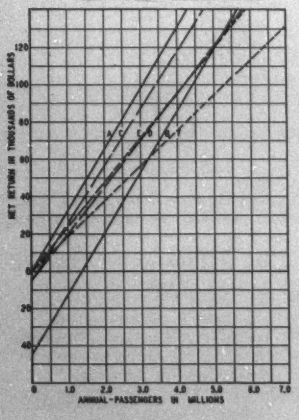


Figure 4. Net return versus annual passengers, five-mile line, L = 0.9, m = 2

Curve designations same as in figure 3

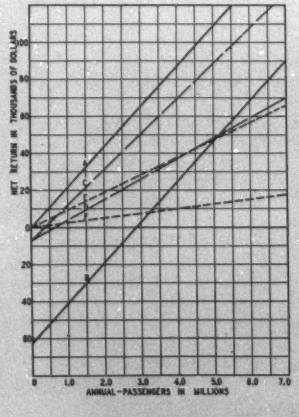


Figure 5. Net return versus annual passengers, seven-mile line, L = 0.9, m = 2

Curve designations same as in figure 3

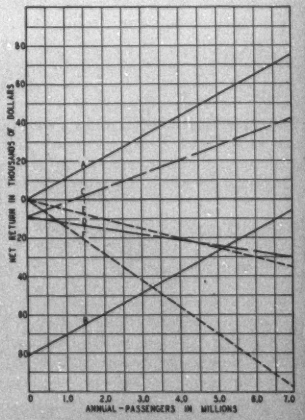


Figure 6. Net return versus annual passengers, nine-mile line, L = 0.9, m = 2

Curve designations same as in figure 3

interest and depreciation; the third term, k_3PUlC_p/V, is the interest and depreciation on the vehicles alone; while the last term $k_4lT/2$, is the interest and depreciation on the new investment in track and overhead, if the street car is under consideration, or the overhead in case of the trackless trolley.

Equation 1 assumes the same schedule every day, including Sundays and holidays. The error introduced only slightly alters the region of best economy for it affects all vehicles to much the same degree. This error could be eliminated by computing separately the annual vehicle-miles for weekdays and for Sundays and holidays, then adding. The additional accuracy obtained would hardly be worth while for the present purpose.

Figure 1 shows typical curves of passengers per hour as a function of the time of day for an existing street-car line. Figure 2 shows the corresponding curves of cars per hour with a 44-passenger vehicle, plotted to the same abscissas. The curves of both figures 1 and 2 were plotted from data taken during a traffic count on this line. For each size of vehicle there are vehicle-demand curves corresponding to those of figure 2.

The connection between the curves of figures 1 and 2, and equations 1, 2, and 3, may be shown as follows: the second term of equation 1 shows that the operating cost is proportional to the quantity t_0C_a, the area under the car-demand curve of figure 2. The daily vehicle-miles, and consequently the operating cost also, are dependent on the length of the line and on the area under the car-demand curve, not upon the shape of this curve, unless of course changing the shape of the curve will alter the average cost of operation per vehicle-mile. The third term of equation 1 contains the term C_p. This is the peak value, averaged over the time of a round trip, of the car-demand curve.

The total number of daily passengers is the area under the passenger-time curve. The total of annual passengers (A) must equal that of passengers per vehicle-mile multiplied by the annual vehicle-miles, or

$$A = \frac{\text{(average vehicle-loading)(seating capacity)}\ \text{(annual-vehicle-miles)}}{\text{(route-miles of line, one way)}}$$

hence

$$A = \frac{2LS}{l}(365lt_0C_a) = 730LSlt_0C_a \qquad (4)$$

Equation 4 shows that for a given vehicle size and loading the annual-passenger total is also proportional to the area under the car-demand curve which is t_0C_a. If the relationship of equation 4 and also that of $C_p = mC_a$ is substituted into equation 1, equation 3 is obtained.

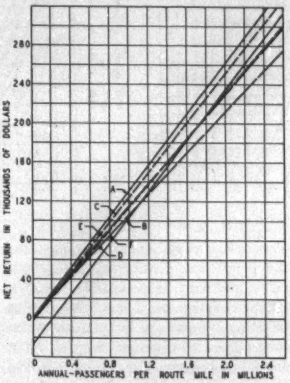


Figure 7. Net return versus passenger density, three-mile line, L = 0.9, m = 2

Curve designations same as in figure 3

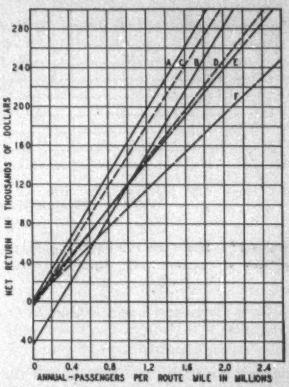


Figure 8. Net return versus passenger density, five-mile line, L = 0.9, m = 2

Curve designations same as in figure 3

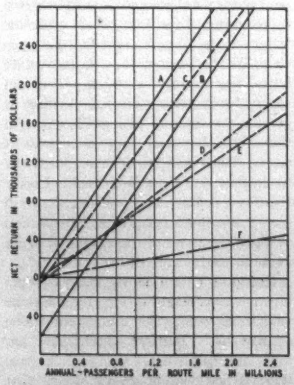


Figure 9. Net return versus passenger density, seven-mile line, L = 0.9, m = 2

Curve designations same as in figure 3

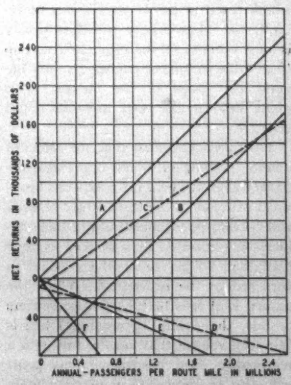


Figure 10. Net return versus passenger density, nine-mile line, L = 0.9, m = 2

Curve designations same as in figure 3

Results. The results of applying the above method of analysis are shown graphically in the following curves.

Figures 3 to 6 inclusive, show the relationship between net return and annual passengers for lines of varying length, assuming a constant average loading of 0.9 and a ratio of average to peak headway of two. In figure 3 are shown, in addition, curves of base and peak headway as a function of annual passengers for the different vehicles. Since the headway, for a given size of vehicle and number of annual passengers is independent of the length of line, headway curves are not shown in figures 4, 5, and 6, for they would be identical with those of figure 3.

Inspection of figures 3 to 6 inclusive reveals a number of interesting facts. For example, the curves show that, if the present track is in such good condition that it will require no more than normal

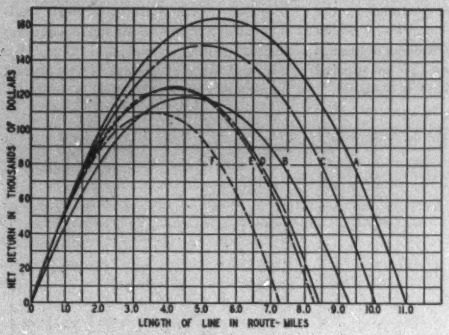


Figure 11. Net return as a function of length of line at constant traffic density, $a = 10^6$, $L = 0.9$, $m = 2$

Curve designations same as in figure 3

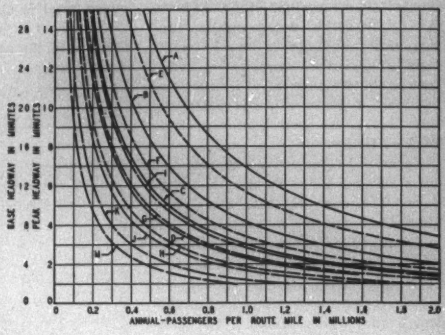


Figure 12. Headway as a function of traffic density

PCC car:

A—three-mile line	*C*—seven-mile line
B—five-mile line	*D*—nine-mile line

44-passenger trackless trolley:

E—three-mile line	*G*—seven-mile line
F—five-mile line	*H*—nine-mile line

22-passenger gas bus:

I—three-mile line	*K*—seven-mile line
J—five-mile line	*M*—nine-mile line

upkeep during the life (20 years) of the new rolling stock, it will be more economical to modernize with new street cars than with any other vehicle. If, on the other hand, the track must be rebuilt at a cost of $65,000[13] per double-track mile, which is about the minimum cost at which track in paved streets can be rebuilt, the 44-passenger trackless trolley is more economical than the street car, up to a value of annual passengers well beyond the range of the curves. This point will be discussed more in detail later.

The curves also show that, for values of annual passengers below approximately 2,000,000 passengers per year, the headways with any of the three larger vehicles will be very poor indeed, unless these vehicles are operated at a smaller average load than 90 per cent, which would in turn reduce the net return. When the annual load falls to 1,000,000 passengers or less, the small (22-passenger) bus is the only vehicle that can be run with a reasonably good headway. This point will also be discussed more completely presently.

Comparison of figure 3 with figure 5 shows that the net return, for a given number of annual passengers, is greater for the three-mile than for the seven-mile line. This result is to be expected, since for the same number of annual passengers, other factors remaining the same, the passengers per vehicle-mile must be larger on the three-mile than on the seven-mile line. But in order to have the same number of annual passengers, the annual-passengers per route-mile must be greater on the short line. This relationship in turn requires that the population density, assuming equal riding per unit of population, must be greater on the short line. A more interesting comparison is obtained, as between lines of different lengths, if the annual-passengers per route-mile, instead of annual passengers, is made the independent variable.

Accordingly in figures 7 to 10 inclusive, are shown curves of net return as a function of annual-passengers per route-mile. The vehicles used, and the other pertinent data, are the same as for figures 3 to 6 inclusive. As will be noted, while the latter curves have essentially the same shape as the former, the relative values have considerably changed. The net return for a given passenger density is greater for lines of intermediate length than for either very long or very short ones. This result immediately leads one to suppose that for a given traffic density there is a definite length of line that will give a maximum net return. Inspection of equation 2 and of the curves of figure 11 confirms this supposition.

In figure 11 are shown curves of net return versus length of line, for the same vehicles as before, for a constant traffic density of 1,000,000 passengers per route-mile per year. For each vehicle there is one definite length of line that will yield the greatest return. This optimum length is greater, the lower the total cost of operation per passenger mile. The curves also show that each vehicle has a maximum length of line beyond which a deficit will appear. This finding agrees with operating experience that long lines are relatively unprofitable unless local traffic is sufficient to keep the passengers per vehicle mile at a profitable level.

In figure 12 are shown curves of headway versus traffic density for 54-, 44-,

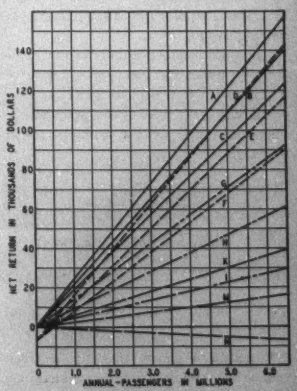


Figure 13. Curves of net return versus annual passengers for different values of the ratio m, seven-mile line, $L = 0.9$

PCC car:

A—$m=1$	*B*—$m=2$	*C*—$m=3$

44-passenger trackless trolley:

D—$m=1$	*E*—$m=2$	*F*—$m=3$

40-passenger gas bus:

G—$m=1$	*H*—$m=2$	*I*—$m=3$

22-passenger gas bus:

K—$m=1$	*M*—$m=2$	*N*—$m=3$

and 22-passenger vehicles, for three-, five-, six-, and nine-mile lines. These curves show that for a given number of passengers per route mile and size of vehicle, the longer the line the better the headways will be. This finding agrees with operating experience. As is common knowledge, it is difficult to give close headways on short lines with any but small vehicles, while on long lines it is relatively easy to provide good headways even with large units.

Effect on Net Return of Changes in Ratio of Peak to Average Number of Vehicles per Hour. In figures 3 to 11 inclusive, the ratio (m) of peak to base cars per hour was assumed to be two, which is almost the exact value for the line of figures 1 and 2. The value of m is a measure of the peak service necessary in terms of the average, and therefore of the required investment in vehicles. For this reason the net return will depend, to a considerable degree, upon the magnitude of m. This will be particularly the case with equipments that have a high first cost or a high depreciation rate.

On light lines where, for the sake of maintaining certain minimum standards of service, considerably better headways are usually provided during the off-peak period than the traffic warrants, the value of m may be less than two. On the other hand, on certain routes serving highly industrialized centers the value may be greater than three.

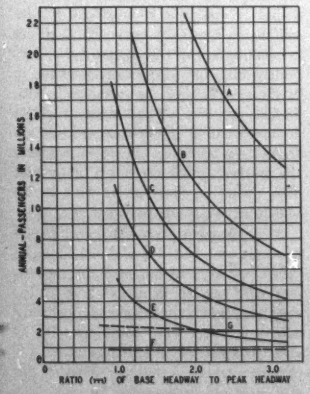


Figure 14. Annual passengers as a function of m for equal net return, L=0.9

PCC car versus 44-passenger trackless trolley, track per double-track mile at:

A—$100,000 *B*—$60,000 *C*—$40,000
D—$30,000 *E*—$20,000

44-passenger trackless trolley versus 40-passenger gas bus:

F—Gas bus at 21 cents per mile
G—Gas bus at 20 cents per mile

Figure 15. Track rehabilitation cost versus annual passengers for equal net returns, PCC car and 44-passenger trackless trolley, L=0.9

A—$m=1$
B—$m=2$
C—$m=3$

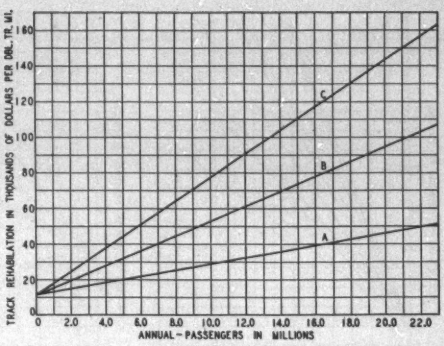


Figure 13 shows the variation in net return with annual passengers for different values of m, so chosen as to cover the range likely to be met with in practice. This figure also shows that the region of best economy for each vehicle also varies with the value of m. As predicted above, the advantage is in favor of the vehicles of low cost and low depreciation rate.

In order to show the region of best economy for the PCC car, the 44-passenger trackless trolley, and the 40-passenger gas bus, the curves of figure 14 were computed. Any individual curve is the boundary line between the regions of maximum economy, under the stated conditions, for the two vehicles to which it refers. To make this point more clear suppose, for example, that a new investment of $40,000 per double-track mile will be needed to rehabilitate the track on a certain existing street-car line that is to be modernized. If the point corresponding to the annual traffic and the value of m for this line is located above and to the right of curve C of figure 14, the street car will give the more economical service; but if the point falls below and to the left of curve C the trackless trolley will give a larger net return. This conclusion does not give the trackless trolley credit for the fact that, because the headways with it will be approximately 22 per cent better than with the street car, it will therefore tend to attract a greater traffic increase.

To illustrate further the use of the curves of figure 14, the line of figure 2 is assumed, for which m is slightly greater than two. This line has an annual traffic of approximately 6,500,000 passengers. Curve C shows that, if a new investment of less than $40,000 per double-track mile is required to rehabilitate the track on this line, the street car will be the more economical; but if the new investment in track must exceed $40,000 per double-track mile, the 44-passenger trackless trolley will give service that is more economical and at the same time more frequent, by approximately 22 per cent.

Figure 15 shows the amount that may be spent in rehabilitating the street-car tracks for equal return with the 44-passenger trackless trolley for different values of m. For example, assume a line that has an annual traffic of 8,000,000 passengers and a value of m equal to three. Curve C of figure 15 shows that if track rehabilitation required an expenditure of less than approximately $64,000 per double-track mile, the street car would be the more economical, but that if the expenditure required exceeded that amount the trackless trolley would be the more economical as well as giving more frequent service.

Importance of Average Loading. In figures 3 to 15 inclusive, the average passengers per vehicle was maintained constant at 0.9 or 90 per cent of the vehicle-seating capacity. Equation 3 shows that a small change in the value of L, the average vehicle loading, will produce a relatively large effect on the net return. This relationship is shown by the curves of figures 16 and 17. The curves show that, for the three-mile line, a 20-per-cent decrease in the value of L (which is another way of saying a 20-per-cent decrease in passengers per vehicle-mile) produces a decrease in the net return that varies from approximately 26 per cent, for the street cars, to about 32 per cent for the 22-passenger bus; while for the seven-mile line the same percentage of decrease in L produces a decrease in the net return that varies between approximately 41 per cent, for the street car, and about 147 per cent for the 22-passenger gas bus. This shows the great importance—one might almost say the

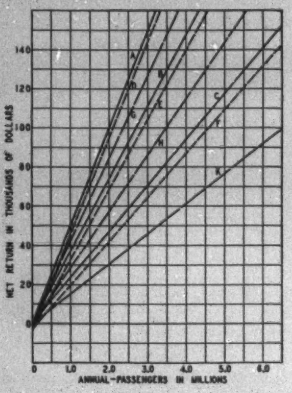


Figure 16. Net return as a function of annual passengers at constant values of vehicle loading; three-mile line, m = 2

PCC car, no track rehabilitation:
A—*L* = 1.0 *B*—*L* = 0.8 *C*—*L* = 0.6
44-passenger trackless trolley:
D—*L* = 1.0 *E*—*L* = 0.8 *F*—*L* = 0.6
22-passenger gas bus:
G—*L* = 1.0 *H*—*L* = 0.8 *K*—*L* = 0.6

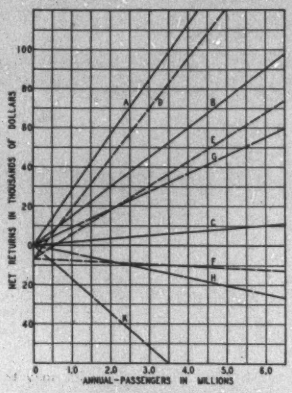


Figure 17. Net return as a function of annual passengers at constant values of vehicle loading; seven-mile line, m = 2

PCC car, no track rehabilitation:
A—*L* = 1.0 *B*—*L* = 0.8 *C*—*L* = 0.6
44-passenger trackless trolley:
D—*L* = 1.0 *E*—*L* = 0.8 *F*—*L* = 0.6
22-passenger gas bus:
G—*L* = 1.0 *H*—*L* = 0.8 *K*—*L* = 0.6

necessity—of keeping the average loading high, particularly on long lines with vehicles that have relatively high operating costs per passenger mile.

This more than proportional change in net return with a given change in loading, is one factor that makes possible, in certain cases—principally with light lines—replacement of a larger vehicle with one of less capacity, thus giving a more attractive headway, and still operating at a profit. During periods of light load, with the same or better headway, the small vehicle will be more nearly loaded, thus raising the value of the average passengers-per-vehicle-mile.

The factors involved can perhaps be most conveniently illustrated by use of an actual example. Figure 18 shows the relationship between passengers-per-hour and the time of day for an existing 6.9-mile street-car line having an annual traffic of approximately 1,745,000 passengers. It is proposed to modernize this line, using the vehicle that will give the best all-around performance. Figure 5 indicates that this line can probably be operated most economically with a 44-passenger trackless trolley, unless the track is in such good condition that an investment of approximately $25,000 per double-track mile will restore it to normal; in this case the PCC car would be the most economical. But reference to the headway curves of figure 3, which also apply to figure 5, indicates that the possible headways, with either the 44-passenger trackless trolley or the PCC car, will not be particularly good, certainly not good enough to attract any considerable amount of additional patronage. This result immediately suggests the desirability of using a smaller vehicle if such a course can be justified economically.

Figure 19 shows vehicle-demand curves for units of the several sizes made up from the traffic curves of figure 18. For the most part the curves of figure 19 provide very liberal schedules. In no case would passengers have to stand during the midday period. This insurance is highly desirable if increased riding is to be encouraged, particularly during the off-peak period. Also the maximum headway was set at 20 minutes, excepting only after 11:00 p.m. After 11 the headway is 30 minutes. The same schedule was assumed for both directions of travel.

Because of the large difference in traffic in the two directions on this line it is difficult to keep the average vehicle loading at a good figure without at the same time forcing some passengers to stand, in the heavy direction of travel, even during the off-peak period. The operating results to be expected for the various conditions and vehicle sizes are set out in table II. Line 1 of table II shows the forecast for the PCC car, assuming an average track rehabilitation cost of $20,000 per double-track mile. If the required expenditure for track rehabilitation is greater than approximately $24,500 per double-track mile, the street car will incur a deficit.

Line 2 of table II shows the projected results for the 44-passenger trackless trolley, with present traffic and a vehicle-demand as shown by curve *C* of figure 19. By decreasing the headways after 7:00 p.m. to values more nearly in line with the traffic after that time, and one or two other minor adjustments in schedule, the $899 deficit may be converted into a net gain of $6,556.

Line 4 shows the results to be expected if the new equipment is able to attract a ten-per-cent increase in traffic. This item shows very strikingly the improved results with even a very moderate gain in patronage. Items 5, 6, and 7 are the same as items 2, 3, and 4, except that they apply to the 40-passenger gas bus. Curve *C* is liberal enough so that a ten-per-cent, and better, increase in traffic can be accommodated without an increase in facilities.

Items 8 and 9 are for the 30-passenger trackless trolley. The first is for present traffic; the second assumes an increase in traffic of 15 per cent (15 per cent is assumed because of the better headways offered by the smaller vehicle). With the 15-per-cent increase in patronage it would be desirable to augment the facilities, as shown by curve *B*. The net return, with the 30-passenger trackless trolley and the 15-per-cent increase in traffic, is $10,502 as compared with $9,571 for the 44-passenger trackless trolley with a 10-per-cent increase in traffic. In addition, the headways with the smaller vehicle are much better and also, owing to fewer stops with it, its schedule speed would be higher.

A 30-passenger gas bus that cost $8,000 per unit and had a useful life of eight years (not 6⅔ as assumed for the 40-passenger gas bus in figures 3 to 17 inclusive) would have to have an operating cost of not over 16.87 cents per mile, in order to equal the performance of the 30-passenger trackless trolley. Whether the gas bus could be operated for only 1.37 cents more per mile than the trackless trolley is doubtful. However, the gas bus would have a decided advantage, in that express service could be provided during the peak period without additional complication or expense; something not possible with the trackless trolley.

The small or 22-passenger gas bus, at 14.25 cents per vehicle-mile, shows a deficit on this line, unless the loading is kept

Table II

Item Number	Vehicle	Schedule Curve From Figure 19	Annual Passengers	Headway in Minutes: Peak	Headway in Minutes: Mid-day	Headway in Minutes: Evening Early	Headway in Minutes: Evening Late	Average Loading in Per Cent of Vehicle Seating Capacity	Passengers Per Vechicle Mile	Annual Miles Per Vehicle	Net Return in Dollars	Remarks
1	54-passenger PCC car	D	1,745,000	8.5	20	20	30	66.2	5.19	30,455	2,769	Track at $20,000 per double-track mile
2	44-passenger trackless trolley	C	1,745,000	6	15	20	30	68.6	4.37	26,297	*899	*Deficit
3	44-passenger trackless trolley	Not shown	1,745,000	6	15	30	30	76.3	4.86	23,643	6,556	
4	44-passenger trackless trolley	C	1,919,500	6	15	20	30	75.4	4.81	26,297	9,571	10 per cent traffic increase over (2) above
5	40-passenger gas bus	C	1,745,000	6	15	20	30	75.3	4.37	26,297	*2,228	*Deficit
6	40-passenger gas bus	Not shown	1,745,000	6	15	30	30	83.8	4.86	23,642	6,234	
7	40-passenger gas bus	C	1,919,500	6	15	20	30	83.0	4.81	26,297	8,242	
8	30-passenger trackless trolley	A	1,745,000	5	12	20	30	81.9	3.56	27,305	3,248	
9	30-passenger trackless trolley	B	2,006,750	4.6	10	20	30	86.5	3.75	27,701	10,500	15 per cent traffic increase over (2) above
10	30-passenger gas bus	B	2,006,750	4.6	10	20	30	86.5	3.75	27,701	4,472	15 per cent traffic increase. 30-passenger gas bus at $8,000 each. Eight-year life. Operating cost at 18 cents per bus mile

high. To accomplish this, passengers must stand in the heavy direction of travel, even during part of the midday period. This is very undesirable if off-peak riding is to be encouraged. The traffic on this line is too large for the most economical operation of the 22-passenger unit.

Undoubtedly the 30-passenger trackless trolley is the proper vehicle to use on this line, unless the cost figures for the 30-passenger gas bus are more favorable than is indicated above.

The above analysis shows very clearly the comparatively large gains in net return due to even small increases in patronage. Therein lies one of the opportunities of modernization. Experience has shown that where service is improved, increased riding results. The best way to improve service, particularly on light lines, is to decrease the headways by substituting smaller, faster, more economical units, operated on closer schedules. In many cases where this has been tried, the results[3] obtained have been remarkable. Lines that were otherwise unprofitable have been converted into money-makers. This is the field for the small bus, and accounts in part for its growing popularity.

The above analysis also shows the importance of adjusting schedules so as to keep the vehicle loading as high as possible, consistent with good service. It shows too what is meant by "operating the smallest vehicle possible within the economic limitations".

Operating Cost. As was mentioned previously, the operating cost, exclusive of interest and depreciation, is the most important of the items of expense in the operation of a transit line. Its importance is indicated by the curves of figures 20 and 21. These show, first of all, that on a short line the operating cost is relatively unimportant. For example, figure 20 shows that for the three-mile line, if the operating cost of the 22-passenger gas bus is reduced from 14.25 to 11 cents per mile, a change of approximately 23 per cent, the corresponding variation in the net return will be slightly less than 13 per cent.

For a long line the conditions are very different. Even small changes in operating cost produce relatively large variations in the net return. This is particularly true of the small units. These statements can be verified by reference to figure 21, which shows that, for a seven-mile line, if the operating cost of the 22-passenger bus varies over the same range of 23 per cent as assumed above, the corresponding change in the net return will be about 72 per cent instead of 13.

In the curves of figures 3 to 10 inclusive,

Figure 18. Passengers per hour as a function of the time of day

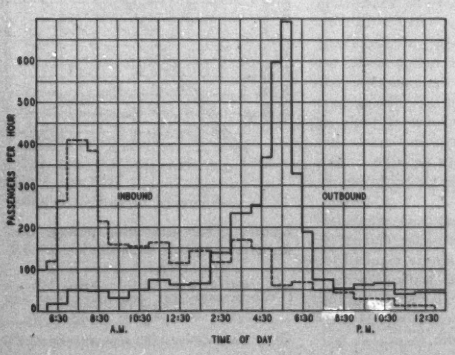
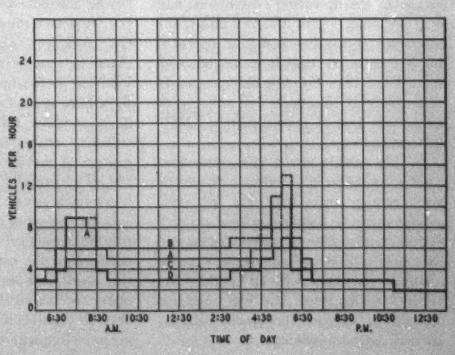


Figure 19. Car-demand curves

A—30-passenger vehicle, present traffic
B—30-passenger vehicle with 15 per cent traffic increase
C—40- or 44-passenger vehicles
D—54-passenger PCC car



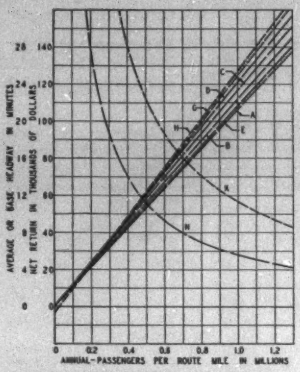


Figure 20. Net return versus passenger density for the small bus, three-mile line, L = 0.9, m = 2

22-passenger gas bus, three-year life, operating cost per mile at:
A—14¼ cents C—12 cents
B—13 cents D—11 cents

22-passenger gas bus, four-year life:
E—Operating cost 14¼ cents per mile

44-passenger trackless trolley, ten-year life, operating cost per mile at:
G—18⅛ cents H—17⅓ cents

K—Headway, 44-passenger trackless trolley
N—Headway, 22-passenger gas bus

the operating cost of the small bus is taken as 14.25 cents per bus mile. This value should be conservative for this unit; in fact some transit companies[13] have operated it for approximately 11.75 cents per mile, exclusive of taxes, interest, and depreciation.

The importance of a low operating cost is strikingly illustrated by the curves of figure 21. This figure shows that an increase in the normal life of this vehicle from three years to four years has about the same effect on the net income as a decrease in the operating cost of one-half cent per mile. Also, it shows that if the 22-passenger gas bus could be operated for ten cents per mile it would be more economical than the 44-passenger trackless trolley at 18.5 cents per mile, up to an annual load of approximately 5,000,000 passengers.

If this vehicle could be operated at such a low figure its usefulness would be very greatly increased. For instance, service would be possible on lines of much lighter traffic than is now economical. Of course, a decrease in operating expense is equally important with any of the other vehicles. The small bus was used for illustration because the results with it are perhaps more striking.

The fact was mentioned previously that to keep equipment in service too long is unprofitable. The small bus is more likely to fall under this rule than any other vehicle. For the conditions shown in figures 20 and 21 the average annual mileage per vehicle amounts to approximately 42,000. On the basis of three years of life, the annual interest and depreciation per unit amounts, at $2,200 each, to $843. If at any time the difference in operating cost per mile between the old and a new bus amounts to as much as two cents per mile, the saving in operating cost will be enough to pay the interest and depreciation on a new vehicle.

A much more important consideration is that patronage falls off if the vehicle is kept in service too long. As was indicated previously, only a very small drop in patronage would be required to reduce the net return by an amount equal to the carrying charges on a new vehicle. Obviously it is unprofitable to keep old equipment in service too long, particularly since new equipment generally brings an increase in riding. With the more expensive equipments obsolescence and decreased riding would make the change desirable long before increased operating costs would have a very great effect.

Capital Costs. In figure 22 is shown for a representative case the amount of new investment required for varying values of traffic density. The curves show that the small bus requires by far the least investment of any of the vehicles considered. For the others the investment required, in vehicles alone, is not greatly different; but when the cost of the overhead for trackless trolley, and of the track and overhead for the street car, are added, the required investment, especially for the street car, may be greatly increased.

Conclusions

The first conclusion to be drawn from the previous discussion is that if the present track has a useful life remaining equal to that of new rolling stock, the PCC car is the most economical vehicle to use in modernizing an existing line; if in addition the volume of traffic is sufficient to warrant a reasonable frequency of service with so large a unit, the PCC car will also probably be the best vehicle to use.

If on the other hand track rehabilitation is necessary, then—the choice depending on the expenditure required for this work and on the traffic density—either the trackless trolley or the gas bus may be more economical as well as offering more frequent service.

Figure 14 shows that, if the track must be completely rebuilt at a cost of approximately $60,000 per double-track mile, the 44-passenger trackless trolley is more economical than the PCC car up to values of annual passengers of approximately 5,500,000, 7,000,000, and 11,000,000, corresponding to values of m of four, three, and two respectively.

Five and one-half million passengers per year is fairly heavy traffic. The heaviest line in Seattle has an annual load of approximately 6,500,000 passengers with a value of m equal to practically two. (The curves of figures 1 and 2 are for this line.)

In a given case the above conclusions may be modified by a full consideration of the psychological factors involved. The quantitative relations may also be altered if the various costs are appreciably different from the values used above.

The principal advantage of the street car is its ability to handle heavy traffic, with sharp peak loads. In this connection it should be mentioned that at about the time this study was nearing completion one of the vehicle manufacturers announced a new rubber-tired vehicle,[14,15] available either as a trackless trolley or as a Diesel-electric bus, of practically street-car capacity. As no cost data were available on this vehicle it is not included in this report. But if, as would be expected, first cost, operating cost, depreciation, etc., for this unit are in line with corresponding costs for the smaller trackless trolleys now in use, the curve for this vehicle could be expected to occupy a

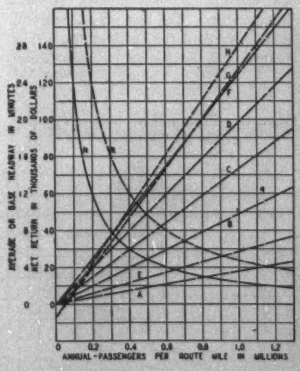


Figure 21. Net return versus passenger density for the small bus, seven-mile line, L = 0.9, m = 2

F—22-passenger gas bus, three year life operating cost per mile at ten cents

Other curve designations same as in figure 20

place, in figures 3 to 13 inclusive, very close to the curve for the PCC car without track-rehabilitation cost. If this should prove to be the case, and if the operating characteristics of the new vehicle are also satisfactory, the street car has a worthy competitor in the heavy-traffic field.

Unless some new development should bring much cheaper track, or a marked drop in interest rates occurs, it is probable that, as present tracks wear out, economic pressure will force the gradual retirement of the rail car from all except the very heaviest surface lines.

The future role of the trackless trolley and of the gas bus is not quite so clear, but for the near future the backbone of the transit system appears to be the trackless trolley, with gas busses on the lighter lines. Figure 14 shows that with an operating cost of 18½ cents per mile for the 44-passenger trackless trolley and of 21 cents per bus mile for the 40-passenger gas bus, the trackless trolley is the more economical for all values of traffic greater than approximately 800,000 passengers per annum. If the operating cost of the gas bus can be reduced to 20 cents per mile the point of equal return is raised to approximately 2,000,000 passengers per year. Evidently the position of the line separating the regions of best economy for these two vehicles is very sensitive to small changes in the relative operating costs. The relative position of these two vehicles could be expected to vary considerably in different sections of the country due to differences in fuel and power costs.

Undoubtedly the future will bring additional improvements in both vehicles that will reduce operating costs. The Diesel-electric is a step in this direction for the self-propelled vehicle. Whether the Diesel-electric, or perhaps the Diesel with hydraulic transmission, will be able to partially or completely supplant the electric vehicles remains to be seen. One influence that will tend to prevent this replacement is the fact that the trend in power rates is steadily downward while that of gasoline and oil prices is up.

The previous discussion also shows the importance of good engineering and good management in a prospective modernization program, not alone in selecting the most suitable vehicle for each line, but also in adjusting schedules and maintaining service so that riding will be encouraged.

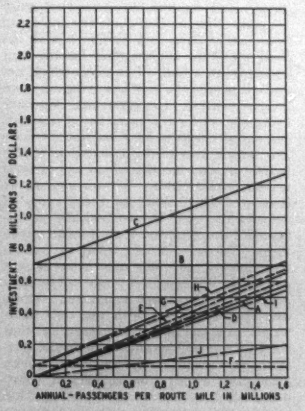


Figure 22. Investment required versus traffic density; seven-mile line, L = 0.9, m = 2

A—PCC car, vehicles only
B—PCC car, track only
C—PCC car, total
D—44-passenger trackless trolley, vehicles only
E—30-passenger trackless trolley, vehicles only
F—Trackless trolleys, overhead only
G—44-passenger trackless trolley, total
H—30-passenger trackless trolley, total
I—40-passenger gas bus
J—22-passenger gas bus

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14. Biggest Yet, *Transit Journal*, volume 82, number 7, July 1938, pages 252–3.

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Discussion

G. M. Woods (nonmember; Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): Professor Hoard's paper is a valuable document to those engineers who are faced with a decision as to the type of vehicle to use for particular transit conditions. The study of the problem from the patron's standpoint as well as the economic standpoint is particularly desirable. The ability to attract new patronage and, by merit, to retain it must be the primary objective of any transportation system. Frequently economies in operation have been carried too far, with the result that gross revenues have decreased more rapidly than operating expenses. Fortunately, the modern vehicles and equipment available are not only more attractive to the passengers but they also are more economical to operate than the older vehicles.

Care must be exercised in a study of this type to avoid drawing general conclusions from a specific example. All of the conditions surrounding any particular application must be carefully analyzed and the correct basic data determined. The paper points out the material effect on the "regions of best economy" of relatively minor changes in operating cost.

Not only must present conditions be considered but thought must be given to the future also. For instance the author assumes a useful life of 20 years for street cars, 10 years for trolley coaches, 6⅔ years for the larger motor busses, and 3 years for the 22-passenger busses. The price which must be paid for replacement vehicles at the end of 3, 6, or 10 years is unknown, although it is an important factor in long-term planning. As brought out in the paper the downward trend of power rates is in favor of electrically propelled vehicles.

L. C. Josephs, Jr. (Mack Manufacturing Corporation, Allentown, Pa.): Perhaps the most important factor in the choice of transportation equipment is the matter of merchandising and not engineering. There has perhaps been too much engineering in some places and not enough attention paid to the merchandising of transportation. The engineering side is apt to look on such factors as the cost of operation, without paying enough attention to the rather indefinite question of what makes people ride and how can more of them be made to ride.

In a general way, the engineering side of transportation equipment has to do more with the cost of operation, whereas the merchandising side of transportation has to do more with the question of gross income. Sometimes to get the optimum difference between income on one hand and operating expense on the other hand, it is necessary to do things that may seem wrong from a strictly engineering standpoint. That, however, is just what some of the railroads are doing on their modern streamlined trains,

where more attention is being paid to showmanship and less to operating economies. Maybe in this present day it is necessary to use considerable showmanship to get the people to ride on the urban transit systems.

H. E. McWethy (Twin City Rapid Transit Company, Minneapolis, Minn.): In discussing this paper I would first like to commend Professor Hoard on the thoroughness with which he has handled the technical aspects of a complicated problem. It is not easy to condense in so short a paper all of the diversified factors which should be and must be given consideration in the determination of the most economical type of vehicle to serve efficiently and safely the requirements of the riding population of any given community. While it is evident throughout the paper that Professor Hoard has had in mind the application of his general solution to the needs of the city of Seattle, Wash., it is also evident that the principles which he has set forth and the manner of solving the problem has a rather universal application to the street-railway systems of the United States. It is no disparagement to the excellence of this paper to say that many of the principles set forth therein have been used by the transportation industry in one form or another in the solution of similar problems for a considerable number of years. This is the first time, however, that we have had the advantage of having these methods set forth as a coordinated whole amply illustrated by the use of graphs.

I presume that our local engineers in the Twin City area would be happy if in this discussion I could take the graphs and formulas presented by Professor Hoard and apply them to the operations of the local transportation system of Minneapolis and St. Paul and thus determine just what should be done with this system. Obviously in a short discussion such an accomplishment is impossible. However, without attempting to reach definite conclusions, I would like to leave certain thoughts for your consideration which came to me as I went over this paper attempting roughly to evaluate our own performance in the light of the methods of analysis proposed in this paper.

At the outset Professor Hoard's analysis gives little if any consideration to the economy of the continuation of equipment which is at present in use on a given system. He assumes that all existing equipment has reached the point where it is uneconomical to continue its use further and that the choice of the transportation industry lies only with the PCC car, the trolley bus, and the gasoline bus. So far as our own system is concerned, we believe that this conclusion as to existing equipment being obsolete for the purpose of solving our transportation problems is not entirely warranted. We have reason to believe that the newer types of equipment must prove themselves by demonstrated economies over the equipment at present in use. In our case unless the newer types of equipment can demonstrate a much greater attractiveness to the public than the equipment at present in use, thus increasing the riding habit materially, there can be little question, so far as our entire system is concerned, as to the net economy of the continuance of the existing equipment in service. Quite rightly, we believe, Professor Hoard dismisses the question of increased riding which would follow the adoption of the new equipment as controversial and a matter of individual opinion, and he assumes for the purpose of his analysis that no change in the riding habit would follow the adoption of a different type of vehicle.

Having reached this conclusion, the remainder of the problem lies in the decision as to whether or not it is more economical with present patronage to continue in operation existing equipment than to adopt one or more of the three types of equipment which are suggested by Professor Hoard.

To justify the increased fixed charges on new equipment purchased there must be quite a marked differential in performance between the old and the new equipment. This differential may take the form of increased speed, greater comfort and convenience of passengers, or lower maintenance costs. The need for the new type of equipment will be most apparent on those properties where this differential between the old and new equipment is greatest. On properties where the differential is least no justification for a change may exist. We feel that the equipment on our property offers a case in point. Certain it is that good economics would frown on the adoption of stream lines without perceptible increase in the comfort and convenience of passengers, and it seems also fundamentally true that to destroy useful remaining life of well-maintained equipment without securing in the new equipment increased benefits of equal or greater value would be likewise unsound. We feel at the present time that the only case where the adoption of a new vehicle is warranted on this system is where a large section of track and paving on an existing line is worn out and must be replaced. In such a case the adoption of a rubber-tired vehicle may be more economical than the continuance of existing rail service.

When we come to compare operating data experienced on this system with that assumed by Professor Hoard, we find on the whole that a close similarity exists. For instance, in table I of his paper he shows 23 cents per car-mile as the average operating cost (excluding depreciation) for the PCC car. The comparable figure on our system for 1938 was 21.8 cents. For our busses which average 26 passengers each, the annual operating cost, exclusive of depreciation, was 15.78 cents per bus-mile, which may be compared with 21 cents per bus-mile which he has used for a 40-passenger gas bus and 14.25 cents for a 22-passenger gas bus.

The average fare per passenger (including transfer passengers) which Professor Hoard assumed of 6 cents compares with the average railway fare on this system of 5.52 cents. (Our record indicates that the average fare per *revenue passenger only* in Seattle approximates 8.3 cents as compared with 7.75 cents, the average fare on this system per revenue passenger.)

Now just a word as to the transportation property which serves the Twin City area. The population served approximates 800,000. The number of street cars is 715, operated on 459 miles of track. These cars operate approximately 21,860,000 car-miles annually and haul in the neighborhood of 100,000,000 passengers annually. This railway operation is supplemented by the operation of 116 gasolite busses which operate approximately 3,800,000 miles annually and carry approximately 4,500,000 revenue passengers. Of the 715 railway cars, all but 35 are unusually heavy cars weighing 44,000 to 50,000 pounds each. Of these heavy cars 459 are equipped with four 50-horsepower motors, and 221 are equipped with four 40-horsepower motors. The 35 lightweight cars average approximately 29,000 pounds, and are equipped with four 25-horsepower motors. These weights may be compared with approximately 35,000 pounds for the average PCC car. Practically all of the heavy cars are equipped with field shunting devices which, while resulting in higher consumption of electricity, have resulted also in increasing our average speed. The average speed of our railway cars for 1938 amounted to 10.72 miles per hour, which according to the American Transit Association records was, I believe, third highest in the nation.

It is true that the heavy cars in use on this property were designed and built 20 or 30 years ago. They were not, however, designed and built as most of the older cars which have been and many of which still are in use on many of the transportation systems of this nation. They appear to have had points of design which still make them more acceptable to our patrons as comfortable-riding vehicles than most of the older cars of other systems to which we refer. Moreover, they have been maintained considerably above the average of those of other systems. They are clean, strong, and comfortable—somewhat noisy we grant—but on the whole the continued operation of these very cars we believe has been one of the factors which has kept our company on a basis of earnings which has made it possible to keep us paying our bond interest and out of receivership. We have every respect for the operation of the PCC car, and although we have had no experience here with it or with the operation of trolley busses, we can see the advantage of their use in certain fields. We are slow to be convinced that either of these types of vehicles can now be economically substituted for the operation of our present equipment. To do so would result in the destruction of a remaining value in our present equipment which we feel would not be compensated for in the new equipment. Moreover, our experience with our own lightweight cars makes us rather skeptical that the PCC car with its small wheels and relatively light weight can give adequate service during our winter months, bucking snowdrifts which accumulate here during these months and contending with the low temperatures which also contribute to the spinning of wheels and the slowing up of service. We have found our own lightweight cars to be inadequate in snowstorms and low temperatures, and conversely we have found that our heavy cars powered with 40- and 50-horsepower motors do maintain our schedules during winter months even though our wheel wear during these months averages six times as great as it does during the summer months of June, July, and August. Under the circumstances, therefore, it appears to us that the substitution of these new types of rolling stock for our present standard cars must be predicated upon our being relieved of the

expense of rebuilding of a substantial section of wornout track and paving in a particular route. Having such a route up for consideration, decision as to whether to substitute trolley busses or gasoline busses must rest upon the principles outlined by Professor Hoard in this paper.

While we may not agree that the time is ripe here for the substitution of some of the newer types of equipment, this very fact can be brought out most effectively by such an analysis as Professor Hoard has presented in this paper.

H. A. Perryman (nonmember; Los Angeles Railway Corporation, Los Angeles, Calif.): This paper has been developed with considerable labor and research and is based necessarily on assumed averages for various operating and traffic factors. As an academic study the paper shows considerable enterprise and has, in my opinion, a decided value in the field of research.

In general, these assumed averages do not apply to this property, with the result that the charts as developed cannot be applied to specific lines operated by the Los Angeles Railway.

The study is based on an average 6-cent fare which is higher than our average fare (4.51 cents) and an average speed of 13 miles per hour which is higher than our average rail speed (10.5). Rates of depreciation and interest are also different.

The study is also based on two assumed averages, which are not often found on our lines, namely L, or the average loading of vehicle, and m, or the ratio of the cars per hour in the peak to the average base cars. Table I of this discussion is a tabulation showing the values of L and m on our rail and principal coach lines.

The study is based on interest rates for new money only, and does not make any allowance for interest on tracks already in place and in good operating condition. As a result of this the values of A in the charts (PCC cars with no track rehabilitation) are somewhat delusive.

The study is based, of course, purely on engineering and/or accounting data and does not take into consideration the operating policy of the company or the popular requirements of the districts to be served.

In planning the modernization of a line or property, the nonengineering considerations, particularly public sentiment with regard to the choice of street car, trolley bus, or bus, are of primary importance.

George L. Hoard: There are in this country transit systems of almost all degrees of preservation. On some systems the equipment is old and run down, with very little useful life remaining. Contrariwise, on others the standards of maintenance are much above the average. Equipment that nominally belongs to a previous generation has been rebuilt one or more times, so that while its appearance may not compare favorably with the latest in modern vehicles, its operating characteristics and cost of maintenance may be reasonably satisfactory. The discussion by Mr. McWethy indicates very strongly that the property of the Twin City Rapid Transit Company falls in the latter class.

This diversity in the condition of present equipment and its associated variables makes it practically impossible to offer a general solution to the question of when will it be more economical to modernize a system or to keep the present equipment in service. Each specific case must of necessity be an individual problem. For this reason, attention is confined in the paper to the case where the present equipment has little useful life remaining.

However, the methods of analysis outlined in the paper are equally applicable where the present equipment may be in good repair. The decision here usually rests on more precarious ground, however, for the reason that if the new equipment is to show a better return than the old it must produce an increase in riding. This increase in riding must be estimated, which is a matter of personal judgment and hence somewhat uncertain at best.

The paper clearly indicates the value of an increase in patronage to a transit system. It also suggests the importance of fast, frequent service with attractive vehicles in encouraging riding. Mr. Josephs, in his discussion, points out the importance of merchandising transportation. Undoubtedly much more attention will be paid to merchandising of transportation in the immediate future. In this respect, the advantages are with modernization. It is much easier to sell transportation with modern streamlined vehicles than with their predecessors. As pointed out in the paper, in many instances where modernization has taken place the results have been so successful that it would have been possible to "write off" considerable in the value of the present equipment and still show a satisfactory financial return.

The figures from the Los Angeles Railway submitted by Mr. Perryman are both interesting and instructive. In general, the value of m will depend to a considerable degree upon community characteristics; for example, a city that is highly industrialized would normally have high peak loads. However, the values quoted are, with a few exceptions, about as one would expect; namely, one or slightly over, for the very light lines, around two or better for the lines of intermediate traffic, while on the heavy lines the value of m is again lower, approaching an approximate average of 1.7.

The value of L, as would be expected, varies over a considerable range being generally low on the light short lines and much higher on the long heavy ones where there would naturally be much local riding.

The figures quoted are particularly interesting in that they illustrate the wide variation in conditions that may obtain on the different routes of a single system, especially if it be a large one. They also indicate the possible danger, as suggested by Mr. Woods, of drawing too general conclusions from specific examples. They further point the necessity for individual study of each line if a complete picture is to be obtained.

Table I. Los Angeles Railway Corporation—Passengers Carried, Load Factors, and Equipment Requirements

	Miles of Route (One Way)	Passengers Carried in 1938 (Thousands)	Passengers Per Mile of Route (Thousands)	Passengers Carried Daily	Number of Trips Daily	Number of Seats	Value of L	Value of m
Rail lines								
A	9.36	9,786	1,046	23,118	396	48	1.2	1.9
B	10.06	10,594	1,053	29,263	356	48	1.7	1.9
D	3.13	1,998	638	4,905	210	44	0.5	1.0
F	12.92	7,736	599	18,073	312	44	1.3	1.8
H	9.62	9,088	945	24,027	403	48	1.2	1.6
I	1.51	609	403	1,360	202	34	0.2	1.0
J	12.54	15,810	1,221	42,690	470	59	1.5	1.6
K	6.44	1,809	281	4,609	156	44	0.7	1.0
L	11.01	12,132	1,102	27,326	409	48	1.4	2.0
N	4.94	6,106	1,236	18,934	326	48	1.2	1.9
O	9.04	6,896	763	16,270	264	44	1.4	1.5
P	10.06	25,877	2,572	63,447	637	59	1.7	1.7
R	11.14	15,397	1,382	38,559	503	48	1.6	1.4
S	12.42	18,163	1,462	42,567	518	48	1.7	1.6
U	13.02	16,675	1,281	43,286	424	44	2.3	1.5
V	12.05	15,585	1,293	36,821	500	48	1.5	2.4
W	15.70	17,605	1,121	45,081	569	48	1.7	1.8
2	6.81	2,816	414	6,636	232	44	0.7	1.1
3	7.00	12,280	1,754	28,293	498	53	1.1	2.0
5	21.80	16,420	753	39,948	508	52	1.5	1.9
7	9.63	8,765	910	21,622	379	48	1.2	1.9
8	8.15	6,863	842	19,028	366	44	1.2	2.1
9	8.37	6,089	727	14,611	325	48	0.9	2.1
10	9.93	5,917	596	13,934	263	44	1.2	1.4
Coach lines								
Through coach lines								
44 Beverly Blvd.	9.19	4,693	511	13,300	478	40	0.7	2.3
47 East 9th-Whittier	7.55	1,700	225	5,700	284	30	0.7	2.1
49 Figueroa	7.22	1,136	157	3,400	210	30	0.5	1.8
Cross-town lines								
41 Alvarado	3.36	2,752	819	7,300	292	30	0.8	1.6
50 Florence-Soto	13.94	7,517	539	21,600	377	30	1.9	2.0
54 Manchester	11.87	1,125	97	3,600	126	30	1.0	1.0
Intermediate lines								
55 Maywood-Bell	7.55	1,747	231	5,200	223	30	0.8	2.0
64 Highland Park	5.97	1,414	254	4,600	195	30	0.8	1.2

L—Average loading of vehicle, that is, the ratio of the average number of passengers per trip to the vehicle seating capacity, in decimals.

m—Ratio (in decimal) of the cars per hour on the peak to the average or base cars per hour.

Power Supply for Resistance-Welding Machines

Foreword

OWING to the tremendous increase in the use of the resistance-welding process during the past several years, and the magnitude of many of the more recent installations, the problem of power supply for these operations has become one of primary importance to all concerned. Resistance-welding machines present an electrical load of intermittent character, high magnitude, and extremely poor load factor, and because of these poor inherent characteristics, the providing of adequate electric service, both from the standpoint of plant electrical distribution and the power system supply, involves special considerations and methods.

The AIEE subcommittee on power supply for welding operations with members representing manufacturers, users, power companies, and the American Welding Society, has been actively studying the various phases of the problem with the fundamental aim in view of bringing about a closer relationship and better spirit of co-operation between these groups in order that each will better understand the problem from the other's viewpoint.

From the viewpoint of the power companies and users, it has been difficult in the past to obtain adequate and reliable engineering data on proposed welder installations prior to their actual installation and operation and, in addition, some of the machines had exceedingly poor electrical characteristics. From the viewpoint of the manufacturers and users, there have been instances where they have been unable to get proper service connections from the power company for handling welder loads. Such refusals to provide service were, no doubt, justified in some cases but others may have been due simply to a lack of interest in the load by the power company and a concern that the load might be disturbing to other customers. Sometimes the user has not adequately prepared for the welder load by the installation of proper bus and transformer facilities with the result that welds are poor and results inconsistent. It is certain that many of these cases of poor co-operation and unsatisfactory installations have been due to a lack of knowledge of all the pertinent facts.

The subcommittee has been working for some time on a series of three reports covering the various phases of the general problem of electric service for resistance welders; two of these are presented herewith:

I. Guide to good electrical performance of resistance-welding machines

II. Resistance-welder installations

Under preparation is:

III. Factory wiring for large resistance welders

It is the hope of the subcommittee that these reports will assist, at least in some small measure, power engineers, industrial plant engineers, welding machine engineers, and any others actively interested in resistance welding in the planning of layouts for welder installations and also in the purchase of new equipment.

Papers 40-57 and 40-58, prepared by the subcommittee on power supply for welding operations of the AIEE committee on electric welding, recommended for publication by the AIEE committee on electric welding, and presented at the AIEE winter convention, New York, N. Y., January 22–26, 1940. Manuscript submitted November 27, 1939; made available for preprinting January 4, 1940; released for final publication February 26, 1940.

Personnel of AIEE subcommittee on power supply for welding operations: L. W. Clark, *chairman;* E. F. Dissmeyer, M. B. Gathman, C. E. Heitman, W. F. Hess, E. A. Hester, H. S. Hubbard, S. M. Humphrey, A. H. Lewis, O. S. Mikhalapov, C. L. Pfeiffer, F. H. Roby, and F. E. Sanford.

I. Guide to Good Electrical Performance of Resistance-Welding Machines*

Purpose of Report

Resistance welding consists of clamping two or more pieces of metal between electrodes and passing electric current through them for the purpose of joining the pieces by fusion of the metal. The adequacy of supply and proper control of this electric current are determining factors in the production of consistently good welds. Relatively high values of current are required at the weld, and the electrical characteristics of the welding machine determine the amount of current which must be drawn from the electric supply lines when delivering these high values of welding current. An efficient machine of good electrical characteristics and low kilovolt-ampere demand requires a much smaller plant investment for transformers, feeders, etc., than the machine with poor electrical characteristics and resulting high kilovolt-ampere demand, although both may deliver the same welding-current output.

This report shows what is meant by good electrical performance and outlines factors upon which good electrical characteristics are dependent. A better understanding of what constitutes such good characteristics will bring about a better appreciation of them by the users of the equipment. Concurrently, as the art advances and the demand for improved designs increases, the manufacturers will meet these demands with continued improvements in their machines. There are several recent developments that eventually may result in radical reductions in demands of resistance welders and a resultant easing of the power-supply problem, but until such machines are commercially and economically available, a thorough understanding of the electrical characteristics of the present-day conventional machines is necessary if they are to be economically served.

It is intended that the report shall assist the purchaser in the preparation of specifications for the purchase of welding machines of the best electrical design, thereby minimizing the problem of power supply. Among the more common types of machines to which it applies are spot, projection, butt, flash, seam, and portable welders.

The report has been made very general in nature and to all who are closely associated with the electrical industry, it may appear that too many elementary factors are discussed, but to production and industrial engineers who represent perhaps the largest single group interested in welding as a production tool, the report should fill a long-felt need in acquainting them with the electrical problems associated with resistance welding.

Scope of Report

The report covers the following subjects:

1. Electrical characteristics of welding machine:
   - (a). Kilovolt-ampere demand
   - (b). Kilowatt demand
   - (c). Power factor
   - (d). Heating
   - (e). Welder primary voltage
2. Power supply and its effect upon welder performance
3. Secondary circuit of welding machine
4. Welder transformer
5. Control equipment
6. Name-plate data for welding machine

* Paper 40-58.

Electrical Characteristics of Welding Machines

The electric current required at the weld is supplied by means of a welding transformer which reduces the supply or plant voltage to a relatively low value (usually less than 20 volts). By this method the current from the supply lines is stepped up to the high value required for welding. The magnitude of actual welding current required depends upon many interrelated factors, such as the type of weld, material being welded, the geometry of the pieces, applied pressure, time of current flow, and perhaps others, all of which are beyond the scope of this report.

The current drawn from the supply lines, while also dependent upon these same factors, is in addition greatly affected by the design and physical arrangement of the welding machine itself. The ratio of the welding or secondary current to the supply or primary current is the best relative measure of the desirable electrical characteristics of two machines of the same secondary current output and the same primary voltage rating. The higher this ratio, the more desirable will be that particular machine, other factors being equal.

Kilovolt-Ampere Demand

The kilovolt-ampere demand is the primary or supply current multiplied by the rated primary voltage and is also approximately equal to the secondary current multiplied by the open-circuit secondary voltage. (The kilovolt-ampere demand as used here in referring to the machine is the instantaneous demand as measured by an oscillograph and should not be confused with the integrated demand of the power meter used for billing purposes.) It bears no relation to the kilovolt-ampere rating of the welding transformer except that it will usually be somewhere between one to about six times as great.

The kilovolt-ampere demand is a direct measure of the desirable electrical characteristics of the machine design—the greater the kilovolt-amperes, the poorer the machine for equal outputs of secondary current.

The kilovolt-amperes taken by a given welder will be a maximum when the electrodes are short-circuited and when the voltage taps are set to give the maximum secondary voltage. When the machine is actually welding, the kilovolt-amperes will always be less than the short-circuit maximum because the impedance of the material being welded causes a reduction in secondary current. If the material being welded is nonmagnetic and of low resistance, such as copper or aluminum, the short-circuit condition is rather closely approximated.

Kilowatt Demand

The kilowatt demand of a welder reveals very little regarding the machine characteristics. (The kilowatt demand as used here in referring to the machine is the instantaneous demand as measured by an oscillograph and should not be confused with the integrated demand of the power meter used for billing purposes.) It represents the energy component of the kilovolt-ampere demand.

Power Factor

The power factor is the ratio of the resistance to the impedance of the welding machine and is also equal to the kilowatt demand divided by the kilovolt-ampere demand. In general, the power factor of a welder should be as high as possible commensurate with satisfactory welding performance. Usually the more efficient and better designed machines will have higher power factors accompanying lower machine impedances and lower kilovolt-ampere demands.

However, high power factor in itself is not necessarily a guarantee of an efficient machine. With the welding electrodes short-circuited, the impedance of the machine measured at the primary terminals of the welding transformer should be as low as possible. This impedance is composed of resistance and reactance and can be reduced by reducing either or both of these quantities. If both are reduced in the same proportion, the power factor will remain unchanged. If the reactance is reduced and the resistance is kept the same, the over-all impedance will be reduced and the power factor increased. On the other hand, if the reactance is not changed and the resistance is increased, the power factor will be increased, but also the over-all impedance will be increased and the efficiency reduced which is highly undesirable. It is, therefore, insufficient to state merely that the machine power factor should be high, because the high power factor might be obtained by the latter method mentioned above. High power factor is advantageous only when accompanied by low over-all impedance and obtained by reduced reactance rather than increased resistance.

The approximate power factor of a machine must be known when calculating the voltage regulation of the electrical supply system due to the welder operation. However, an accurate knowledge of the maximum kilovolt-amperes drawn by the welder is of much more importance than an accurate knowledge of the power factor ratio and, in general, results obtained when using estimated power factors are reasonably satisfactory.

Tests of many flash, butt, spot, and projection welders show that the usual range of power factors for the larger machines (50-kilovolt-ampere rating and up) is between 20 and 40 per cent, and that for estimating purposes the use of 30 per cent power factor, coupled with the known value of kilovolt-ampere demand, will prove reasonably accurate. Similarly, 40 per cent power factor can be used for machines of 10- to 50-kva rating, and 60 per cent power factor for machines under 10 kva in size.

Heating

The heating of the machine is another important consideration due to the fact that the insulation life of the welding transformer is a function of operating temperature. The manufacturer shall provide ample cooling of transformer and secondary loop to prevent overheating at the rated current and duty cycle of the machine. (The duty cycle is the per cent of time that current flows, averaged over a definite period. The length of the period depends upon the class of equipment and is, for example, one minute for electronic control devices.) A duty cycle of 50 per cent has been adopted as standard for rating purposes and the transformer kva rating is an indication of the allowable heating load for which the machine is designed.

Welder Primary Voltage

If possible, the larger welding machines should be supplied from 440 or higher voltage sources due to the fact that the primary current demand is inversely proportional to the primary voltage, everything else being equal. The use of higher voltages assists in keeping voltage drop or regulation at a minimum.

Power-Supply Requirements and Welder Performance

Allowable voltage drop rather than allowable heating usually becomes the limiting factor in determining supply conductors and transformers because of the extremely low operating duty cycles of most welding operations. The supply to the welders should be such that the maximum voltage fluctuation or dip, measured at the last point on the welder bus or distribution wiring which is com-

mon to two or more machines, does not exceed 10 to 15 per cent. (This value of 10 to 15 per cent applies to the welding circuit and is not to be confused with the usual limitation of one to two per cent for lighting circuits affected by the welding load.) It is highly desirable to provide a system which will keep the voltage fluctuation within the ten per cent limit if consistently good welds without an excessive number of rejects are to be expected. In extreme cases the 15 per cent limit might prove satisfactory, and there are conversely some few applications in which the ten per cent limit might be excessive.

The nominal base voltage may vary gradually from time to time throughout the day due to general plant load changes and other factors, and no attempt is made here to specify an allowable range for this gradual shifting of the base voltage. Obviously, if the gradual change is appreciable from, say the day operating shift to the night operating shift, it might become necessary during such periods to change the heat or tap setting on all welding machines to compensate for the changed voltage conditions.

This report does not concern itself with the methods of providing service for welders, except to show the importance of keeping the kilovolt-ampere swings or instantaneous demands at a minimum. A succeeding report entitled "II. Resistance Welder Installations" describes the various commonly used methods of providing service for welders.

Small welder installations are usually served by a power company at either 220 or 440 volts, and the minimum charge for service may be roughly proportional to the magnitude of the maximum kva swing or instantaneous demand and, consequently, it is much to the advantage of the user to purchase a machine with as small a demand as possible.

Welder installations in the large factories, which either have their own power plants or are served by a power company at primary voltages, such as 2,300, 4,800, 6,600, or 22,000 volts, present a similar service problem with the exception that the plant engineer is directly concerned with transformer and distribution bus investment costs needed for the welders.

To show the importance of purchasing a welder of good electrical design, a typical example will be worked out. The welding engineer of a certain plant needs a projection welder with a maximum welding-current output of 100,000 amperes. He gets quotations from different manufacturers on machines incorporating the desired mechanical and control features for handling the particular type of work involved. The final selection eventually is between two competing machines, each having the same mechanical features and same method of control, but with the following differences in electrical rating:

	Machine A	Machine B
Rated kilovolt-amperes of transformer (50 per cent duty cycle)	300	500
Maximum open-circuit secondary voltage—volts	12	20
Maximum secondary current (maximum secondary voltage and minimum throat spacing)—amperes	100,000	100,000
Rated primary welder voltage—volts	440	440

Welder *B* was slightly more expensive than welder *A* but the fact that it had a larger transformer at first glance indicated it to be the best machine. However, a true analysis of the cost of serving the two welders shows that welder *A* is the logical selection. The basic consideration as far as welding ability is concerned, is the secondary current output and the ability of the welder to operate without overheating at a certain prescribed rate of production or duty cycle. Both welders had the same maximum current output and the productive output was guaranteed the same by both manufacturers. The larger transformer simply was needed to supply the excessive losses of machine *B*. The approximate kilovolt-ampere input for machine *A* is:

$$\frac{(100{,}000 \times 12)}{1{,}000} = 1{,}200 \text{ kva}$$

and for machine *B* is:

$$\frac{(100{,}000 \times 20)}{1{,}000} = 2{,}000 \text{ kva}$$

Assuming that a 1,200-kva step-down power transformer is needed to serve welder *A*, it would be necessary to go to a 2,000-kva transformer for machine *B* for the same voltage regulation. At $3 per kilovolt-ampere, this amounts to $2,400 added investment for machine *B* in transformer capacity alone. Conductor costs for bus and distribution are correspondingly greater for the machine with the higher kilovolt-ampere input. The plant engineer who is responsible for costs of service for the welding operations will certainly select welder *A* as the most economical and desirable machine. The welding engineer who is interested primarily in machine output and production, is equally satisfied as both machines are equal in this respect.

In addition, there is always an upper limit of allowable kilovolt-ampere demand, the exact magnitude depending either upon the factory's location with respect to the power company's substations and power lines or the size of its own generating plant.

In case of power company service, the point of connection to the power company's system determines the allowable size of welder that can be handled. The sudden flow of welder current through the system impedance causes a momentary voltage fluctuation which, if of sufficient magnitude, results in lamp flicker for all lighting customers at that and nearby locations. The farther the point of service is from the main generating plants and larger substations, the greater the system impedance and resultant voltage fluctuation for a given size welder. Voltage fluctuations must be kept within accepted limits for lighting customers. These limits vary, depending upon the frequency of the fluctuation and, in some cases, if the frequency is high, such as with certain types of seam welders, the allowable voltage fluctuation may be as low as one-half volt at the lamp, and for ordinary frequencies experienced with spot, projection, and flash welders may be as high as one and one-half to two volts.

Whenever the kilovolt-ampere demand of the welder is great enough to cause lamp flicker at other nearby customers, there are only two fundamental changes which can be made to eliminate the flicker. The system impedance beyond the point of service common to the lighting and welder loads can be reduced or the sudden flow of current through that impedance can be reduced. There are numerous methods for accomplishing either of these changes, such as reducing the system impedance by increasing substation and line capacity, tapping the welder load direct to the transmission system, separating the lighting and welder loads and serving them from separate substation bus sections, or reducing the amount of current by the use of series capacitors, synchronous condensers, phase balancers, or motor generator sets. Most of these methods involve expense of some considerable magnitude which must be passed on to the user of the welder. Obviously, if the purchaser of the welder can select a machine of more efficient design with a kilovolt-ampere demand within the allowed limit for that particular location, such expensive power-

system changes or the addition of corrective equipment would not be needed. It is, consequently, much to the advantage of the prospective purchaser of the welder to obtain in advance of the purchase the allowable maximum kilovolt-ampere demand that the power company can permit at that location and then, if at all possible, select a machine that will produce the desired welding current without exceeding this allowable kilovolt-ampere input.

Welders of large size can usually be served readily in large industrial areas which generally have concentrations of power quite separate from any lighting services. The main business sections of large cities do not usually have distribution facilities suitable for welders and generally the cost of providing service at such locations is prohibitive even for relatively small machines. Suburban areas and small towns are also very likely to be unsatisfactory and expensive locations except for the smaller machines.

Secondary Circuit of Welding Machine

The single, most important factor in keeping the kilovolt-ampere demand low is the design of the secondary circuit of the welding machine regardless of whether it is a spot, seam, or other type of welder.

In order better to understand why this is so, it is only necessary to consider from the fundamental angle what is required to make a given weld. As a simple illustration, suppose a welding machine is required to spot weld two pieces of 16-gauge SAE 1010 cold-rolled steel. From existing engineering records the design engineer would possibly conclude that to obtain the desired quality weld, it would be necessary to limit the time to eight cycles and to pass 12,000 amperes through the parts to be welded.

The next point to be considered is the geometry of the parts to be welded since they, in turn, will dictate the minimum clearance in the secondary circuit of the welding machine which will permit properly placing the parts to be welded between welder electrodes. In this case, perhaps a 12-inch throat depth and 7-inch clearance between horns would readily admit the work to be welded. The next step is to determine the voltage necessary to cause the required 12,000 amperes to flow through this 12-inch by 7-inch secondary circuit with the work in position. This voltage might be found to be four volts which would immediately establish the kilovolt-ampere demand of 48 kva. If, on the other hand, a machine had been selected with a throat depth of 24 inches and a horn clearance of 12 inches because it looked as though it was plenty big enough for the work and would also permit welding a larger job at some future date, a voltage as high as ten volts might have been required to give the 12,000 amperes, thereby imposing a demand of 120 kva on the distribution system and penalizing everyone concerned forever after.

From this it may be concluded that the first rule in obtaining a machine with a minimum demand for a given welding operation is to pick out a machine with a clearance that is just large enough for the work to be done, fully recognizing the fact that if any larger clearance exists, the demand is going to be larger than it need be. There are, of course, cases where the user definitely has need for a larger throat for a certain portion of his work and he must then either put up with a larger than necessary demand on smaller parts or perhaps purchase two machines.

Having determined the throat clearance which is to be furnished in the machine, there are other factors which influence the demand, such as the actual design of the machine having this throat depth. These matters are entirely in the hands of the welding-machine manufacturers and it may be said that they, as a group today, are doing their utmost to reduce the impedance of their welding machine circuits in order to reduce to a minimum possible voltage disturbances in plant-distribution and power-system lines.

The prospective purchaser of welding machines can be assured of the merit of the electrical design of the machine being purchased, by comparing the secondary current outputs and the kilovolt-ampere inputs of the machines being considered. For the same secondary current output the machine having the lowest kilovolt-ampere input will be the lowest impedance machine and, consequently, the most desirable from this angle. The purchaser can also observe the physical geometry of the welding machine parts and select a machine in which the transformer is placed as close to the useful throat of the machine as possible and in which the flexible connections are so arranged as not to introduce excessive reactance.

Portable Welders

In the case of portable welding machines, the same fundamental principles apply. There is here, however, another factor to be considered and that is the type of cable used between the transformer and the gun, assuming, of course, the same principles regarding clearances have been applied to the gun as were mentioned above in regard to the throat of the welding machine. Here it is important that (1) cables no longer than necessary are selected, (2) that in the case of parallel conductors, cables be strapped closely together at all times to reduce the reactance, and (3) that full consideration be given to single, low reactance, interleaved, and concentric designs of cable which are now on the market and which substantially reduce the demand during weld.

Welder Transformer

The transformer incorporated as part of the complete welding machine should be built in accordance with the latest revision of the AIEE Standards No. 39 as soon as this revision can be accomplished. In the meantime the latest Resistance Welder Manufacturers Association Standard, which is a carefully drawn one, can be relied upon. The transformer name-plate rating is based upon a 50 per cent duty cycle and indicates the kilovolt-ampere load it can safely carry at 50 per cent duty cycle. It in no way indicates either useful output of the machine in welding current, or the maximum kilovolt-ampere input to the machine from the supply lines. The equivalent continuous ratings corresponding with loads at various duty cycles are:

70.7 per cent of the load at 50 per cent duty cycle
31.6 per cent of the load at 10 per cent duty cycle
22.4 per cent of the load at 5 per cent duty cycle

Control Equipment

Proper control of a welding machine is essential if consistently good results are to be obtained. Many pages would be required to cover adequately and completely all the various phases of welding-machine control. It is the intention here to simply outline in as concise a manner as possible the fundamental concepts of control requirements, the various types of control equipment, and the field of application for each.

Fundamental Requirements

The energy required to produce a weld is directly proportional to the current squared, the resistance of the weld area between the electrode points, and the time during which the welding current is allowed to flow. To obtain consistent

results, each of these three factors must be controlled as carefully as possible.

The welding current is usually regulated by changing the position of a tap switch on the primary side of the welding transformer or by delaying the ignition of electronic interrupters, thereby reducing the effective voltage applied to the transformer primary. In any case the transformer secondary voltage is raised or lowered to bring about the required change in current.

Contact resistance varies inversely with the pressure applied to the work. On manually-operated or motor-driven machines a limit switch can be set to close at a point equal to satisfactory welding pressure. Operation of the limit switch would initiate the flow of current. The pressure switch, actuated by means of the back pressure built up in the operating cylinder, is usually substituted for the limit switch on air-operated machines. However, an adjustable time delay introduced between the operation of the air valve and the application of power to the work, would accomplish the desired result.

Timing of the interval during which current is allowed to flow is a more difficult problem. Many types of equipment are available for this purpose. In general, the complete installation consists of an interrupter for the power line and some means for predetermining the period during which it is closed.

Types of Equipment

The interrupter may be electronic, motor-driven, air operated, or magnetically operated. To apply recently adopted standard rating curves in the selection of interrupting equipment, it is essential that these factors be known:

1. Transformer maximum primary amperes
2. Required number of welds per unit of time
3. Estimated length of each weld

Control devices are classified as two different types—synchronous and nonsynchronous. The first is generally used where a premium is placed on absolute accuracy. High initial cost and relative complexity discourage universal use.

Nonsynchronous control involves an inherent possible error amounting to at least a plus or minus one-half cycle and possibly more, depending upon the nature of the equipment. In addition, it does not guard against the danger of variable transient current surges introduced by haphazard circuit closing present in nonsynchronous control. These errors become objectionable when applied to short timing periods and when the nature of the work is such that precision control is necessary. The fabrication of extremely small parts and the welding of stainless steel or nonferrous metals are usually within this classification.

A design classification for timers would include mechanical, electromagnetic, electrostatic, or electronic types. Final selection of a specific device should be based on the accuracy required, initial cost, maintenance cost, accessibility, range of adjustment, reliability, and simplicity.

Either the "fixed" or "current responsive" principle of current timing may be used. "Fixed timing" is satisfactory for most applications and results in less complicated equipment. Some few types of work require automatic compensation for variations in work conditions and "current responsive" systems are available for these. The machine supplier or control manufacturer will be acquainted with these requirements.

When air-operated machines are equipped with solenoid-operated valves, a fully automatic timing device performing the following functions can be used:

1. Automatic application of pressure to the work
   (Squeeze Period)
2. Initiation of power flow at time interval later
   (Weld Period)
3. Termination of power flow at the conclusion of the weld
   (Hold Period)
4. Removal of pressure after the weld has cooled
   (Off Period)
5. Reapplication of pressure after the work has been removed and new parts placed between electrodes

A low-voltage (110 volts or lower) push-button circuit is recommended to minimize danger of electrical shock.

If the voltage regulation in the welder supply lines is excessive, a separate supply line for the timer control circuit should be installed. A 110-volt lighting supply circuit is usually available for this purpose. The installation of a fusible control circuit disconnect switch separate from the power switch is considered an operational advantage although separate power and control sources are not always required.

Name-Plate Data for Complete Welding Machine

Power and industrial engineers have been handicapped in the past when called upon to plan and provide service for proposed welder installations because of a dearth of reliable and accurate information regarding name-plate and specification data for the proposed machines, particularly information about maximum kilovolt-ampere demand or load. To improve this situation the following name-plate data should appear on the name plate of the complete welding machine:

1. Manufacturer's name and address
2. Manufacturer's type and designation number
3. Rated kilovolt amperes of transformer (50 per cent duty cycle)
4. Maximum open-circuit secondary voltage
5. Minimum open-circuit secondary voltage
6. Maximum secondary current (with maximum secondary voltage and minimum throat spacing)
7. Rated primary voltage and frequency
8. Manufacturer's serial number

From the above essential name-plate data, the following additional information can be readily calculated:

(*a*). Transformer turn ratio [rated primary voltage (7) divided by maximum open-circuit secondary voltage (4)]

(*b*). Maximum kilovolt-ampere input at rated voltage (neglecting exciting current) [Maximum secondary current (6) multiplied by maximum open-circuit secondary voltage (4)]

(*c*). Maximum primary-current demand (neglecting exciting current) [Maximum secondary current (6) divided by transformer turn ratio (*a*)]

II. Resistance-Welder Installations*

Purpose of Report

Factory wiring and electrical distribution for resistance-welding loads must be designed on an entirely different basis than that for the ordinary power and lighting loads encountered in industrial plants. To provide a sound basis upon which recommended methods of wiring, types of bus construction, and transformer arrangements can be established the AIEE subcommittee on power

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* Paper 40-57.

supply for welding operations has obtained descriptive reports of a number of commercial resistance-welder installations, in plants throughout the country. These reports show the different methods successfully employed in existing installations, and give a clear picture of some of the problems involved. It is hoped that they will serve other users of resistance-welding equipment as a basis upon which new installations can be made.

Design Principles

In reviewing these reports, it should be remembered that the majority of resistance-welding machines have instantaneous kilovolt-ampere demands several times their normal rating, and that in order to prevent excessive voltage drop at this equipment, as well as at any nearby equipment, the supply and distribution facilities must be designed on the basis of the peak kilovolt-ampere demand rather than the normal rating of the machine. From a standpoint of voltage regulation the supply and distribution system must be such as would normally be employed if this peak kilovolt-ampere demand were drawn continuously. However, due to the low operating duty cycle of this load, its heating effect on the system is usually extremely small.

Since the capacity of all power equipment and distribution systems is based on heating or temperature-rise limitations it is seen, therefore, that in order to serve one resistance-welding machine, the normal capacity of the system must be much higher than necessary from a heating standpoint in order to satisfy the conditions of voltage regulation. In fact, in designing a system to supply two or three or even ten welding machines operating on the usual duty cycle encountered, it is safe to neglect the consideration of heating capacity required and design the system to satisfy the consideration of voltage drop. It is only when a considerable number of machines are involved on a single system that the heating becomes a consideration of any importance, or when the duty cycle of a single welder exceeds about 25 per cent, such as with most seam welders.

Summary

In the following representative welder installations, several types of feeder distribution systems are represented. Two of the companies employ a bus system to which the individual welders can be readily and quickly connected or disconnected. Tap points are available at regular intervals and the welding machines can be moved around from season to season with very little expense. The same is true, to a lesser degree, of the wire or cable feeders used by the other companies. This type of feeder does not lend itself quite so readily to frequent changes in plant layout, but is generally cheaper and easier to install.

The bus system employing the concentric arrangement of copper tubes will be found to have the lowest voltage drop, and where this factor is of major consideration this type of feeder is of highest efficiency. In installations where the equivalent thermal loading is high, this type of construction may be unsatisfactory since the heat radiation or conduction from the inside conductor is comparatively low. However, should it become necessary, cooling air can be forced through the inner conductor thus raising its load capacity. The system of interlaced copper bus bars, usually has a high load capacity, but gives a slightly higher voltage drop than the concentric construction.

The system of cable construction is of course the simplest, since the problems of insulation are minimized. In general this type of construction gives a higher voltage drop and lower load capacity than either of the above types. However, if the various conductors are interlaced and spaced very close together the voltage drop can be reduced to a value comparable with the bus-type construction. In so doing the load capacity is reduced due to the reduced radiating surface, and this must be compensated for by a sufficient number of parallel lines to reduce the thermal loading to the safe point.

Table I shows the ratio of total connected welder load to total supply-transformer capacity for the various installations, the ratio of largest single welder to total supply-transformer capacity, and the ratio of resultant thermal load to total connected load. The first ratio in some cases may be determined by the thermal loading of the system and thus be dependent upon the average operating duty cycle of the units comprising the installations. If the average operating duty cycle is high, the thermal loading will be high and this ratio must be low. The ratio of largest single unit to supply-transformer capacity is usually determined by the requirements of over-all voltage drop. If a large part of the permissible voltage drop is consumed in the feeder line, the allowable drop in the supply transformer is small, and this ratio must be small. In most commercial installations it is this consideration of voltage drop that determines the supply-transformer capacity, rather than the consideration of thermal loading.

It will be noted that the ratio of total connected load to total supply-transformer capacity varies from 0.4 to 8.74, but the weighted average is about 2.0. This wide variation may be partly explained by the fact that the method of rating resistance-welding equipment has, in the past, been rather vague, and the values of connected load taken from the name-plate ratings may be

Table I. Summary

Company	Feeder	Phases	Power-Transformer Capacity	Connected Load	Type of Service	Ratio Total Connected Load to Total Supply-Transformer Capacity	Ratio Largest Single Welder to Total Supply-Transformer Capacity	Ratio of Thermal Load to Total Connected Load
A		Three	3,000	4,500	Flash	1.5	0.25	0.118
B	*A*	Single	1,000	2,000	Projection, flash, and seam	2.00	0.50	0.10 for all feeders combined
B	*B*	Single	2,000	1,700	Projection and butt	0.85	0.375	0.10 for all feeders combined
B	Top	Single	2,000	1,960	Flash and projection	0.98	0.3	0.10 for all feeders combined
B	Center	Single	2,000	2,750	Flash and projection	1.375	0.3	0.10 for all feeders combined
B	Bottom	Single	2,000	1,250	Projection and flash	0.625	0.3	0.10 for all feeders combined
C		Single	1,500	13,119	Miscellaneous	8.74	0.3	0.048
D		Three	1,000	1,500	Seam	1.5	1.5	0.67
D		Single	1,260	500	Projection	0.4	0.4	0.44
D		Single	840	750	Spot	0.89	0.89	
E		Single	666	1,585	Spot and seam	2.35	0.60	
F		Three	1,500	2,400	Miscellaneous	1.6	0.267	0.177

quite at variance with the now commonly accepted practice of rating equipment on the basis of a 50 per cent duty cycle. For example under company *C*, section 6, we see that a normal current of 300 amperes applies to four different sizes of equipment, namely 50, 75, 100, and 150 kva.

The minimum value of 0.4 applies to a projection welder operating from a special supply transformer, and supplied by means of a concentric-cable feeder. Obviously the major consideration in this case is that of voltage drop.

The maximum value of 8.74 applies to an installation having a relatively large number of units. In such an installation the probability of a large number of units operating simultaneously is rather remote, so that from a standpoint of voltage drop, the required capacity of the supply-transformer bank is determined by the size of the largest single unit. In this instance the ratio of largest single unit to supply-transformer capacity is 0.4.

Another factor which makes for low supply-transformer capacity, in this case, is the use of the low-impedance concentric tubular bus. This type of bus gives a comparatively low voltage drop, so that a higher impedance (lower capacity) supply-transformer bank can be tolerated. The chief reason for the ability of company *C* to serve 13,119 kva of welding load with only 1,500 kva of supply-transformer capacity, is their use of a good concentric bus design with extremely low impedance. This permits serving an exceptionally large factory area by the single-bus system without obtaining excessive voltage drop at the welding equipment. Other types of bus construction and cable assemblies cannot serve as large an area, nor as many units, without excessive voltage drop. The result is that where such construction is used there must be more feeders operating in parallel or a higher supply-transformer capacity.

Where a large number of smaller units are to be served, the thermal loading of the supply transformers and feeder lines may become the determining factor. This determination, however, depends upon a knowledge of the operating duty cycles of the various equipments. In this particular case the average operating duty cycle is comparatively low, the ratio of average kilovolt-ampere load to connected kilovolt-ampere load being 4.8 per cent. The ratio of average kilovolt-ampere load to supply-transformer capacity is approximately 0.4, the extra capacity being necessary to limit the voltage regulation.

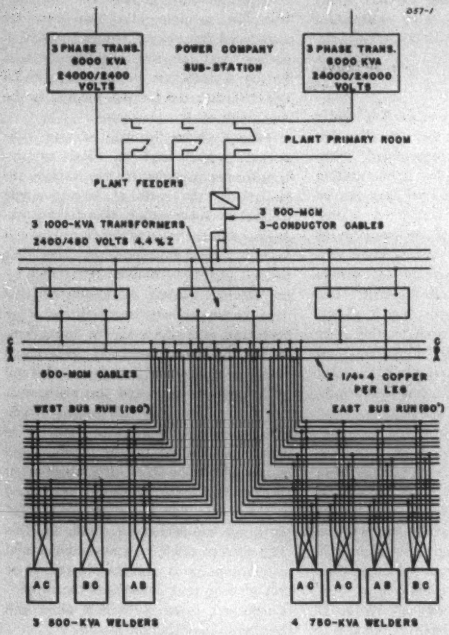

Figure 1. Schematic diagram of welder supply system—company A

The ratio of largest single unit to supply-transformer capacity varies from 0.3 to 1.5, with a weighted average of about 0.5. The maximum value of 1.5 applies to a seam-welder installation in which the thermal loading of the system is the determining factor in selecting supply-transformer capacity.

The ratio of thermal load to total connected welder load for these commercial installations of all types except seam welders is between 0.048 and 0.177, and for seam welders, between 0.44 and 0.67.

It must be remembered that it is impossible to give any definite empirical values for any of these ratios, since the proper values depend upon individual conditions. The values given in table I do, however, give a general idea as to the practice followed in some of the industry's successfully operating installations.

It is interesting to note that in all of these installations overload protection of the feeders and transformers is confined to instantaneous overcurrent devices, designed to protect against short circuits. In one installation this instantaneous tripping is reduced well below the short-circuit current to provide a measure of protection against high overloads on individual welders. The protection thus afforded against individual machine overloads is very small. In so far as we are informed, the only practical overload protection is that afforded in the connections to each individual machine. This may take the form of instantaneous overcurrent trips, overtime trips, or a combination of these two, or some thermal relay or fuse with thermal characteristics similar to the equipment to be protected.

For the protection of supply transformers, the instantaneous overcurrent devices set for short-circuit currents have proved satisfactory. In installations where the thermal loading is high, contact-making thermometers immersed in the cooling oil have been employed to trip the circuit breakers when the oil temperature becomes excessive.

Another point of interest is that the power supply for the resistance-welding loads is usually separated from the general plant power supply. Generally speaking the voltage disturbances produced by the resistance-welding load cannot be tolerated on other plant loads, particularly lighting. For this reason

an attempt is made to minimize these disturbances by separating the two loads as much as possible.

Installations—Company A

1. Method of Service by the Power Company

The power company provides service for all plant load, including the resistance welders, through a step-down substation consisting of two 6,000-kva three-phase transformers connected 24,000/-2,400 volts, located on the plant property as near as practicable to the load. Each transformer is radially fed by means of an underground cable from a 24,000-volt substation located about one-quarter mile from the plant. The transformer secondaries are solidly connected to the 2,400-volt bus. The 2,400-volt plant feeders are connected to the bus through oil circuit breakers and double-throw disconnecting switches, as shown in figure 1.

2. Cost to the Power Company to Serve Welder Load

No special consideration or expense was required by the power company to serve the welder load. The step-down substation was needed to supply the load at the voltage required, and the 24,000-volt supply to the substation was of ample capacity to take the kilovolt-ampere swings of the welder without producing troublesome flickers.

No other customers are fed from this step-down substation and so the power company has not been concerned by the flicker on the 2,400-volt bus. If, in the future, some new load develops in this area that could advantageously be fed from this substation, it might be necessary to set aside one substation transformer for welders and other flicker-producing load and use it also as the "throwover."

3. Plant Distribution for Welders

The welder power transformers which supply the welder bus are three 1,000-kva single-phase 2,400/480-volt 4.4 per cent impedance, connected delta-delta in a three-phase bank. They are fed from the primary room by three 250-foot lengths of 500,000-circular-mil three-conductor cables, operating in parallel. The transformers are located on the roof near the load center of the welders. The 480-volt transformer bus is made up of two one-quarter- by four-inch copper bars per phase. Solidly connected to the transformer bus are 12 three-phase feeders of three single-conductor 500,000-circular-mil cables distributed over the entire bus. These feeders are brought down from the transformer bus on the roof to the welder room in four groups of three three-phase feeders. Each group is supported in wooden cleats and taped together. In the welder room, the four groups of three feeders divide into two groups of six feeders each. One group extends about 80 feet east and the other about 160 feet west from the transformer bus. The three conductors of each three-phase feeder are taped together and supported from messenger cable strung from the building girders above the line of welders. Each welder is connected to the same phase of each of the six three-phase feeders so as to divide the load about equally among the six feeders. The different welders are connected to the three phases so as to have about an equal load division on the three phases.

4. Cost Data on the Welder Feeder

Low cost was obtained by the use of the same size copper (500,000 circular mil) throughout.

5. Welder Feeder Protection

All connections are solid from the oil circuit breakers in the primary room to the welder. The oil circuit breaker is automatic and set for time-delay trip on overload.

6. Type and Rating of Welders

The welders are all flash welders of which four are rated 750 kva and three are rated 500 kva.

7. Voltage Drop

Voltage-drop data given below are calculated values in per cent based on a single-phase load of 800 kva of welding current at 0.4 power factor, 480 volts.

1. At 24,000-volt bus in power company substation.....0.7
2. At 2,400-volt bus in plant switch house.....2.3
3. At 480-volt transformer bus.....4.7
4. At welder, including 65-foot welder bus.....5.0

The voltage drop for the above four items is accumulative and represents the total drop to each point. To find the drop in any particular part of the system, for example, the drop from the 480-volt transformer bus (item 3) to the welder over 65 feet of bus (item 4) is 5.0 per cent minus 4.7 per cent equals 0.3 per cent.

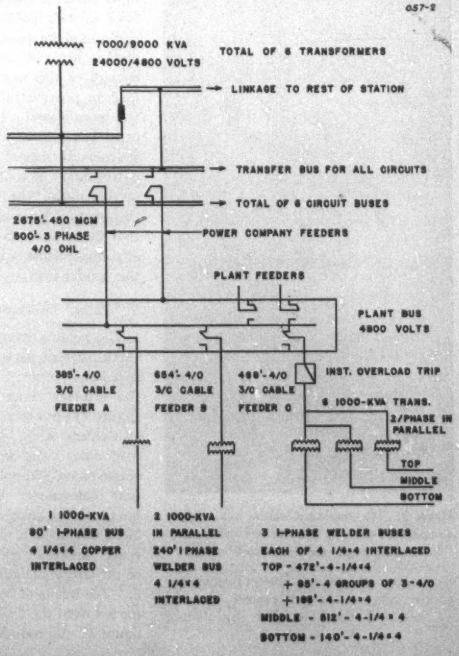

Figure 2. Schematic diagram of welder supply system—company B

8. Equivalent Thermal Loading

The heating load on the welder feeder obtained by maximum-demand heater-type ammeters was approximately 128 amperes per phase at 2,400 volts, which was 530 kva. The heating load in per cent of total connected welder kilovolt-amperes is 530/4,500 equals 11.8 per cent. At the time these readings were taken, it was known that only 3,500 kva of welders were actually operating. The heating load in per cent of operating-welder kilovolt-amperes was 530/3,500 equals 15.2 per cent.

Company B Installation

1. Method of Service by the Power Company

This plant is fed by two 4,800-volt power lines out of a 24,000/4,800-volt step-down substation as shown in figure 2. The step-down substation consists of six 7,000/9,000-kva 24,000/4,800-volt three-phase radially fed transformers, serving six 4,800-volt circuit busses. Each transformer is linked to the rest of the substation through reactors and a linkage bus. The circuit busses occupy the lower position of a double bus arrangement with a transfer bus above. The transfer bus is a continuous section energized from the linkage bus.

The plant primary room bus is also a double-bus arrangement with a power line feeding each bus. The welder feeders are operated on the "throwover" bus and general plant load on the other bus.

Figure 3. The interlaced welder bus used by company B, showing construction and method of making taps for individual welders

Bus consists of four one-quarter by four-inch copper bars on one-inch centers, insulated by means of five one-eighth by six-inch Micarta strips

2. Cost to the Power Company to Serve Welder Load

Originally the power line supplying the welder load was connected to a circuit bus at the substation with only power load. On such a bus the flicker limit is three volts (at lamp voltage) which would permit 1,500-kva load swings. The plant later increased the size and number of welders until load swings exceeded 2,000 kva and caused voltage flickers of four to five volts, and complaints from other customers on this bus.

There were sufficient spare positions at the substation so that it was possible by rearranging and transferring lines to set aside one circuit bus for this welder load. At present this circuit bus carries only the load of this one power line, but the transformer is still connected to the other busses through the linkage. If the load in this substation area increases and the spare positions on this bus are needed for new load, it may be that enough of this new load will be flicker load to provide satisfactory loading for the transformer. This has happened at other substations where a bus has been set aside for special load. Another alternative might be to use the spare positions on this bus as "throwover" lines to other customers. It is not felt in this case that the power company has been put to any appreciable added expense to serve this welder load.

3. Plant Distribution for Welders

The welding transformers are located at three different parts of the plant and are supplied by three 4,800-volt feeders from the primary room. Feeders *A* and *B* (figure 2) serve general plant load as well as welders, while feeder *C* serves welder load only. The welders are tapped to single-phase 480-volt busses made up of four one-quarter by four-inch copper bars with the going and return bars interlaced on one-inch centers with a Micarta spacer between each bar and on each side of the entire assembly as shown in figure 3. The bus is of open construction supported from the building pillars shown in figure 4. To reduce the chance of short circuits from foreign material falling across the bars, the Micarta spacers extend about one inch above the bars. Data on each of the feeders are given below:

Feeder A

1. 350 feet of three-conductor 4/0 cable from primary house to transformer

2. Supply transformer—one 1,000 kva, single phase, 4,800/480 volt, 4.6 per cent impedance

3. Feeder bus—80 feet four one-quarter by four-inch copper bars interlaced

Feeder B

1. 654 feet of three-conductor 4/0 cable from primary house to transformers

2. Supply transformers—two 1,000 kva, single phase, 4,800/480 volts, 4.6 per cent impedance, two in parallel

3. Feeder bus—240 feet four one-quarter by four-inch copper bars interlaced

Feeder C

1. 468 feet of three-conductor 4/0 cable from primary house to transformers

2. Supply transformers—six 1,000 kva, single phase, 4,800/480 volt, 4.6 per cent impedance (two transformers in parallel on each phase)

3. Feeder bus:

Top bus—472 feet of four one-quarter by four-inch copper bars interlaced plus 85 feet of four interlaced groups of three 4/0 cables, each on about four-inch centers to another bay and there 185 feet of four one-quarter by four-inch copper bars interlaced

Center bus—512 feet of four one-quarter by four-inch copper bars interlaced

Bottom bus—140 feet of four one-quarter by four-inch copper bars interlaced

4. Cost Data on Welder Feeder

The welder bus cost was $10.50 per foot installed.

5. Welder Feeder Protection

There is no protection provided on feeders *A* and *B*. The oil circuit breakers in the primary room are nonautomatic. The oil circuit breaker of feeder *C* is automatic and set for instantaneous tripping on overload. The power company's incoming line is also provided with an automatic instantaneous-tripping oil circuit breaker, so it is doubtful if a worthwhile degree of selectivity is obtained between the plant feeder *C* breaker and the power company's breaker.

6. Type and Rating of Welders

The type, number, and rating of the welders on each bus are given below:

Feeder A

Projection, flash, and seam	6
Total connected load (kva)	2,000
Largest single unit (kva)	500

Figure 4. Two separate interlaced welder busses used by company B, showing method of support

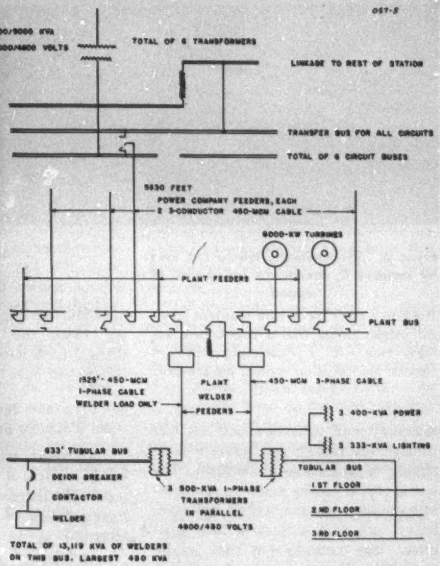

Figure 5. Schematic diagram of welder supply system—company C

Feeder B

Projection and butt	9
Total connected load (kva)	1,700
Largest single unit (kva)	750

Feeder C

Top Bus

Projection and flash	11
Total connected load (kva)	1,960
Largest single unit (kva)	600

Center Bus

Projection and flash	11
Total connected load (kva)	2,750
Largest single unit (kva)	600

Bottom Bus

Projection and flash	3
Total connected load (kva)	1,250
Largest single unit (kva)	600

Test data have been obtained on two of the largest welders used.

1. 600-kva projection welder; maximum swings, 960 kva, 2,110 amperes, 450 volts at 0.347 power factor at welder (1,000 kva at substation)

2. 750-kva welder; maximum swings, 1,760 kva, 4,300 amperes, 418 volts at 0.299 power factor at welder (2,100 kva at substation)

7. Voltage Drop Caused by Welder Load

The voltage drop in per cent at various points has been calculated and is based on a load of 2,100 kva at 480 volts, 0.4 power factor.

1. At substation, 4,800-volt bus	3.5
2. At plant primary-room 4,800-volt bus	6.4
3. At welding-transformer primary	7.1
4. At welding-transformer secondary (two 1,000 kva in parallel)	11.8
5. At welder over 100 feet of four one-quarter by four-inch bus	13.0

The voltage drop for the above five items is accumulative and represents the total drop to each point. To find the drop in any particular part of the system, for example, the drop from the welder transformer secondary (item 4) to the welder over 100 feet of bus (item 5) is 13.0 per cent minus 11.8 per cent equals 1.2 per cent.

8. Equivalent Thermal Loading

There are no available data on thermal loading on the individual feeders. For the total connected load of 9,660 kva, the average kilovolt-amperes or thermal load is approximately 900 kva, or slightly less than ten per cent.

Company C Installation

1. Power Company Method of Service

The step-down substation from which this plant is fed consists of six radially fed three-phase transformers of 7,000/9,000 kva, 24,000/4,800 volts, feeding six 4,800-volt circuit busses as shown in figure 5. The transformers are linked by reactors on the 4,800-volt side. The circuit busses and transfer bus form a double bus arrangement, with the transfer bus tied to the linkage bus. The short-circuit kilovolt-amperes on each 4,800-volt circuit bus is 147,000 kva.

Each power line to the plant consists of two cables of 450,000 circular mils and supplies a separate bus at the plant primary house. In addition to the power-company supply, there are two 6,000-kw turbines at the plant which operate in parallel with one power-company line.

2. Power Company Cost to Serve Welders

The substation bus supplying this plant can stand 1,500-kva swings without exceeding the flicker limit of three volts on the substation bus. This limit has never been exceeded, and so there has been no additional expense to serve the welder load.

3. The Welder Feeders

There are two welder feeders, but since their construction is nearly identical detailed description will be given for only one of the feeders.

This feeder consists of 1,525 feet of 450,000-circular-mil single-phase cable from the primary house to three 500-kva 4,800/480-volt transformers connected in parallel. The 480-volt welder bus is connected solidly to the transformer

Figure 6. The concentric tubular bus used by company C, construction and method of support

The bus is made up of bare four-inch standard copper tubing over a three-inch extra-heavy tube with a Micarta-tube separator. Taps for the individual welders are provided every six feet

secondary and extends about 633 feet through the factory and serves a large number of production-type welders. The bus is copper tubing made up of a four-inch standard tube over a three-inch extra heavy tube with a Micarta tube separator. The outer tube is bare, solidly grounded, and supported by the building girders (figure 6). There is a tap provided on the bus every six feet. The De-ion breaker contactor and timer for each welder are located on a rack by the welder bus (figure 7). The lead into each welder is made of special cable with the control wiring laid in the main cable. This cable required no conduit.

4. Welder Bus Cost

The cost of the tubular bus, made up of four-inch standard tubing over three-inch extra-heavy tubing in 12-foot sections with taps every six feet is about $9 per foot. Installation cost is extra and will depend somewhat upon local conditions.

This company uses two-inch standard tubing over one and one-quarter-inch extra-heavy tubing on the branches of the second welder bus, but no figures are available on its cost.

5. Bus or Feeder Protection

Faults on the welder bus or the 4,800-volt supply are cleared by the oil circuit breaker at the primary house. The breaker is tripped after a time delay by an induction-type overcurrent relay and is selective with the main supply breaker from the power company. Each welder tap has a De-ion type air breaker which is a two-pole breaker with the poles in parallel. This gives it a rating of 190 amperes and an interrupting rating of 10,000 amperes. The breaker is set for instantaneous tripping at about eight to ten times the breaker rating. The thermal trips were found to be unsatisfactory and have been disconnected.

6. Type and Rating of Welders Served

This feeder serves a total of 13,119 kva of welders of various types and ratings. The list given in table II is fairly representative of the types and sizes served.

7. Equivalent Thermal Loading

The following readings were obtained during normal production on the feeder which supplies welders only:

Connected kva	13,119	
Normal peak kva	880	
Average load kva	610	
Average load kw	304	
Average power factor	304/610 =	49.8 per cent
Average kva/connected kva	610/13,119 =	4.8 per cent

8. Voltage Drop Caused by Welder Load

Voltage drops in per cent are:

1. At the substation bus, 4,800 volt . . 2.5
2. At the plant primary house, 4,800 volt 3.8
3. At the welder transformer primary, 4,800 volt 4.5
4. At the welder transformer secondary, 480 volt 8.7
5. At the welder over 633 feet of bus . . 11.3

The above figures are calculated for 1,500-kva 0.4-power-factor, 480-volt welder load supplied by one power-company line and do not take into account any assistance obtained from the plant generators.

The voltage drop for the above five items is accumulative and represents the total drop to each point. To find the drop in any particular part of the system, for example, the drop from the welder transformer secondary (item 4) to the welder over 633 feet of bus (item 5) is 11.3 per cent minus 8.7 per cent equals 2.6 per cent.

Figure 7. Showing welder bus and controls used by company C

The controls are mounted on racks alongside the bus, and consist of De-ion circuit breaker, welding contactor, and timer for each welder

Company D Installation

There are at present 269 resistance welders installed in this plant, with the following name-plate ratings:

Number of Welders	Rating (Kva)
51	Under 5
70	5 to 25
25	30 to 50
60	60 to 100
26	125 to 175
26	200 to 300
6	350 to 400
1	500
2	600
1	750
1 five head	1,500

Electronic control is used wherever accurate timing and synchronous switching is required. In installations requiring less accurate control, ignitron contactors are now being used in place of the former standard magnetic contactor in order to cut down service costs.

Practically all the welders are at present protected by enclosed fused switches. Where control equipment and switch are located at a distance from the welder, it is customary also to include a line contactor operated from a tumbler switch at the welder. In future, however, enclosed air circuit breakers will be used with all but the smaller units. These breakers will be either manually or electrically operated, depending on their location in respect to the welders, and will have instantaneous overload trips, in some cases with an additional undervoltage trip coil operated by a thermal overload relay incorporated in the welder control.

From the standpoint of power supply, these welders may be divided into three classes, as follows:

CLASS I

This includes resistance welders of all types, both with and without electronic control, which are installed as separate units and obtain power from the regular 575-volt three-phase 60-cycle shop lines. With the exception of a few spot or projection welders, the name plates of which may be as high as 350 kva, these welders are not rated over 150 kva or, in the case of multiple-head machines, the individual welding heads do not exceed this limit. About 94 per cent of the resistance welders are in this class.

Before connecting a welder to a shop line, consideration is given to the effect of voltage drop, caused by the actual power demand during weld, on other load supplied by that line. Inasmuch as most of the lighting load is on d-c or separate a-c lighting feeders, it is possible to permit fairly large momentary voltage variations on the a-c shop feeders without undesirable results. Figure 8 shows a typical section of the 60-cycle distribution. This distribution system is designed to supply shop load, and neither its cost nor design has been directly affected by welders of this class.

Table II. Type and Rating of Welders—Company C

Type	Kilovolt-Ampere Rating	Normal Current	Maximum Current	Rated Current at Rated Volts
Gun	50	150	550*	114
Gun	75	300	500	170
Hydromatics	100	300	550*	228
Hydromatics	150	300	800*	340
Spot and projection	450	5,000	6,000*	1,000
Spot and projection	50	300	650*	114

* Estimates based on test readings. This company generally figures five to eight times rated kilovolt-amperes for momentary load.

The central substation *A* from which the primary feeders of this system radiate has a capacity of 30,000 kva with a calculated bus short-circuit value of 500,000 kva. Primary power is distributed at 13.8 kv three phase, grounded neutral, over 17 feeders, most of which are rated 4,800 kva and consist of three-conductor 4/0 15-kv cable. Each feeder has a five per cent current-limiting reactor which limits feeder short circuits to approximately 100,000 kva. Relaying of feeder oil circuit breakers is for short-circuit protection only. These feeders serve 24 substations each of which has an emergency tie to at least one other than its normal feeder.

Substations vary from 1,800 to 3,500 kva in transformer capacity, the more recent transformer units being 1,500 kva instead of the 600 kva shown in figure 8. Although the 800-ampere 600-volt manually operated oil circuit breaker has been standard for 575-volt feeder protection, air circuit breakers will be used in any new substation construction. This also applies to shop entrance panels.

Secondary feeders are 575 volt, three phase ungrounded, and consist usually of one three-conductor 500,000-circular-mil cable nominally rated 400 kva. If more capacity is needed a similar cable is added in parallel or a separate feeder is established. Length of feeder between substation and building may be up to 1,000 feet. Inside building feeders usually are of open construction extending the length of the building and may be anywhere from number 0000 to 1,000,000 circular mils in size. It is obvious that the larger welders in this class cannot be fed from the more remote sections of the shop 575-volt lines, and as mentioned above, each case must be considered in the light of the particular line capacity and demand involved.

CLASS II

This covers group installations of welders where the voltage disturbances set up by the operation of one or more of the welders, if from the shop 575-volt lines, would interfere with the operation of other welders of the same group. In some cases such installations can be supplied from the nearest substation through a special low-impedance line, but in two installations the following methods have been used.

The first group consists of 14 seam welders and one projection welder four of them having two welding transformers each (figure 8). Name-plate rating of the group is 2,524 kva, 550 volts. The 19 electronic controls required, together with their protective equipment, are mounted together on a centrally located overhead platform. Directly below the platform is installed a Pyranol-filled transformer rated 1,000 kva, 13,800/-575 volts. The low-voltage side of this transformer is connected to a short bus directly underneath the platform floor, from which connection is made through

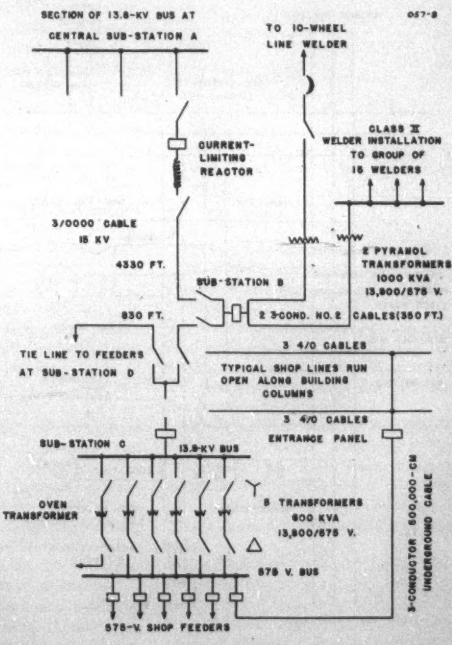
SECTION OF 13.8-KV BUS AT CENTRAL SUB-STATION A
057-8
TO 10-WHEEL LINE WELDER
CLASS II WELDER INSTALLATION TO GROUP OF 18 WELDERS
CURRENT-LIMITING REACTOR
3/0000 CABLE 15 KV
4330 FT.
2 PYRANOL TRANSFORMERS 1000 KVA 13,800/575 V.
SUB-STATION B
830 FT.
2 3-COND. NO. 2 CABLES (350 FT.)
TIE LINE TO FEEDERS AT SUB-STATION D
3 4/0 CABLES
TYPICAL SHOP LINES RUN OPEN ALONG BUILDING COLUMNS
3 4/0 CABLES
ENTRANCE PANEL
SUB-STATION C
13.8-KV BUS
OVEN TRANSFORMER
5 TRANSFORMERS 600 KVA 13,800/575 V.
575 V. BUS
3-CONDUCTOR 500,000-CM UNDERGROUND CABLE
575-V. SHOP FEEDERS

Figure 8. Schematic diagram of typical welder supply system—company D

two-pole fused enclosed switches to each separate welder and control. Each welder control is also equipped with a two-pole contactor, operated from a tumbler switch at the welder, which opens the power circuit to the welder without removing control voltage from its control panel. With all welders operating under normal production, the actual load, as measured with indicating instruments, is 1,116 kva, three phase, with a maximum unbalance between phases of 12½ per cent, and an average 0.45 power factor. (Note that these are short-throat welders.) Bus voltage averages 549 volts with a maximum variation plus and minus of 3½ per cent. It is probable that the average kva load over a period of several hours is slightly below the measured amount which may explain why there is no trouble with overheating the 1,000-kva power transformer.

A second installation directly adjoining the above consists of one seam welder equipped with five welding heads each with a 300-kva name-plate rating. Control consists of electronic panels mounted on an extension of the above-mentioned platform. Power is obtained from a second 1,000-kva three-phase Pyranol-transformer similar to the one mentioned above and located directly below the platform. The low-voltage side of this transformer is connected through a manually operated disconnecting switch and a 1,200-ampere three-pole inverse-time-limit electrically operated enclosed air circuit breaker directly to the five welding circuits and controls. Excitation for the controls is fed through an enclosed fused switch tapped into the line ahead of this breaker so that the breaker, which is operated from a push-button station at the welder, may be opened without breaking the control excitation. Under normal operation this welder demands approximately 1,500 kva with a 66 per cent duty cycle (two cycles on, one off) and draws, as measured with indicating instruments, 1,006 kva, three phase, with a maximum unbalance between phases of 22 per cent and an average 0.50 power factor. Supply voltage averages 525 volts with the welder in operation, and 550 volts at no load, with a plus and minus variation at either point of two per cent.

The primary power supply to these two installations is taken from one of the regular shop 13.8-kv feeders *A* indicated in figure 8.

The control panel for the 13.8-kv oil circuit breaker is located on the welder control platform. Connection to the high side of each transformer is through pothead-type terminals which in turn are protected by an additional steel enclosure.

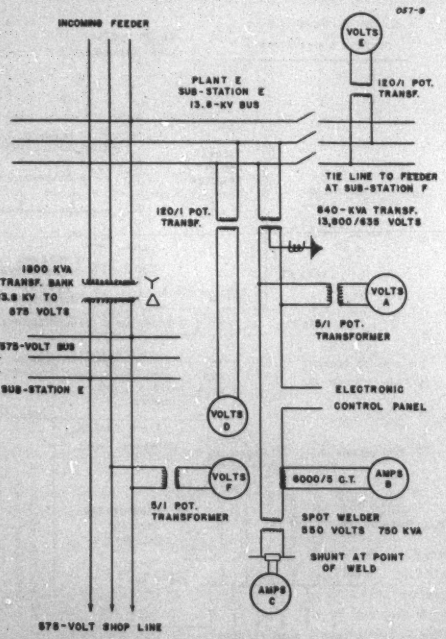

Figure 9. Location of voltage and current readings taken during test of power-supply system with 750-kva spot welder in operation —company D

Class III

This includes large electronically controlled projection or spot welders where, although the equivalent continuous load is not great, the line-current demand at the time of making the weld is so high that it is inadvisable to supply it from the regular power transformers of one of the shop substations. In general, this applies to welders having a demand in excess of 2,000 amperes root mean square, 550 volts, during weld.

There are at present two installations that illustrate this classification. The first is a projection welder rated 550 volts, 500 kva (50 per cent duty cycle). Power for this welder is brought through a two-conductor 750,000-circular-mil concentric cable 500 feet long, from a special transformer. This transformer is rated 1,260 kva, 13,800/287.5-575-1,150 volts, and is designed to supply 15,000 amperes (peak) when connected for 575 volts. Maximum current obtainable at the welder is 2,200 amperes root mean square during weld with about 70 volts drop in the line.

The second welder in this class is a spot welder with name-plate rating of 550 volts, 750 kva, equipped with electronic control arranged for interrupted-operation welding. Power is obtained from a special transformer rated 840 kva, 13,800/635 volts and designed to give an impedance drop of less than 15 per cent when loaded at 6,000 amperes, 0.60 power factor. This transformer is located outside the building about ten feet from the welder and is fed from the 13.8-kv bus of the nearest shop substation through two lines of a three-conductor 15-kv underground cable approximately 210 feet long. This substation is in turn fed by a 13.8-kv feeder 3,800 feet in length, similar to the one shown in figure 8. Protection for both the welder and the power transformer is by an oil circuit breaker located in the shop substation and controlled from a panel adjacent to the welder. Both thermal and instantaneous overload relays are provided. Also the midpoint of the 635-volt winding of the power transformer is grounded through a current transformer which operates an instantaneous relay of low current setting to trip the circuit breaker in the event of a ground in either the welder transformer or control. The low-voltage side

of the power transformer is directly connected to the control and welder through a two-pole manually operated disconnecting switch.

Recently tests were made to show the effect of the operation of this welder on various parts of the power system. The welder was operated at maximum capacity with a duty cycle of 4 cycles on and 54 off. All readings were taken simultaneously on an oscillograph with the following results. Figure 9 indicates the points at which these readings were taken.

A. Voltage of 603-volt supply to welder dropped 21.9 per cent (note that drop as read on indicating voltmeter was only 4.5 per cent).

B. Current of 603-volt supply to welder was 4,800 amperes (root mean square during weld).

C. Current in weld was 90,600 amperes (root mean square during weld).

D. Voltage of 13.8-kv bus in substation *E* at point of feed to welder power transformer dropped 9.7 per cent.

E. Voltage of the 13.8-kv tie line to substation *F* dropped 4.4 per cent. This indicates the drop on the central substation bus as this tie line is energized from a 13.8-kv feeder different from the one supplying the welder. Note that the capacity of the supply to the central substation bus was one-half normal at the time these tests were made.

F. Voltage of the 575-volt shop lines in plant *E* supplied through wye-delta-connected transformer bank substation *E* dropped 6.7 per cent.

All readings but the last were definitely taken from the same phase. It should be noted that the general plant voltage drop of 4.4 per cent (in one phase) observed at *E* is reduced one-half when the central substation bus is operating with full-capacity supply, and is probably further reduced by the time it reaches the 575-volt distribution system by the balancing effect of synchronous- and induction-motor shop load.

Company E Installation

In this plant like in many others where acquisition of new equipment and general expansion have been gradual, the majority of the welding equipment is widely scattered all over the plant. Furthermore, because of the nature of the plant's business, drastic changes in the location of a large portion of the welding equipment available are quite frequent. When they occur, certain general shifts in power loads and temporary feeds are sometimes made which result in different power-supply conditions.

For these reasons to present a general picture of the power feed of all welding equipment used would be both difficult and inconclusive. Accordingly this report is limited to a description of power supply of one group of welders which, because of the time and permanency of their installation, can be treated as an integral unit.

General Description of Equipment

The resistance-welding equipment comprising this group consists entirely of spot and seam welders. All but two are of the pedestal stationary type. One is a fully portable welding gun and one a semi-portable type with provision for 30-foot travel. All stationary machines are located within 50 feet of the distribution board.

The kilovolt-ampere capacities of the equipment are shown in figure 10. It will be noted that several of the machines have full-load capacities of such magnitude that were they to form part of the normal production load unsatisfactory voltage regulation would result with the power supply available. However, the maximum production requirements of these machines are considerably lower, as shown on the "normal maximum" line, and rather than increase the power-supply installation mechanical provisions are made preventing the setting of these machines at a tap higher than the normal maximum for all work except experimental which is conducted by plant engineers only when this group is inoperative, and with one machine at a time.

Load Conditions

The total maximum load is 1,375 kva. This load, however, corresponds to operation with short-circuited secondaries. The actual working loads of these machines run 5 to 15 per cent less, depending on the machine and the material used. Assuming an average of 10 per cent, the actual maximum load becomes 1,237.5 kva. Application of this load to the 460-volt bus results in a net drop of 13.6 per cent on this bus which would be excessive from the welding point of view. In addition it produces a 5 per cent drop on the 2,300-volt bus which is also considered undesirable.

However, the application of maximum load presupposes two facts: (1) that every machine is operated at its maximum setting; (2) that every machine should fire at the same time. As the machines are operated most of the time at setups averaging 50 per cent capacity, and as the combined duty and welding cycle (time of flow of current to total operating time) is between 5 per cent and 25 per cent, the probable maximum load is considerably smaller.

Prolonged and extensive oscillographic studies of the group failed to reveal load peaks higher than 500 kva with a highest daily average around 250 kva.

No attempt has been made to measure the kilowatt or kilowatt-hour loads as no evidence of heating of transformers, equipment, or feeders has ever been observed.

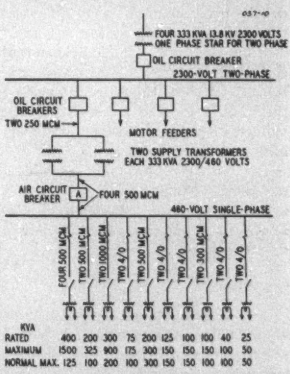

Figure 10. Schematic diagram of welder supply system—company E

Power Supply

The power is supplied by two 333-kva 2,300/460-volt single-phase 3.56 per cent impedance oil-immersed self-cooled transformers connected in parallel. The transformers are installed on an outdoor platform adjacent to the floor housing the welding equipment. The 460-volt bus and distribution are thus not over ten feet from the transformer bank.

The transformer bank is fed from a 2,300-volt bus which, in addition to the welding load, also feeds a miscellaneous motor load averaging about 300 kva, two phase, with a normal maximum 15-minute demand of around 650 kva, two phase.

The 2,300-volt bus is fed by a 930-kva, two-phase transformer bank (belonging to the power company) consisting of four 333-kva 13,800/2,300-volt single-phase oil-immersed self-cooled transformers, star connected.

Distribution System

The 2,300/460-volt transformer bank is fed from the 2,300-volt bus by two 250,000-circular-mil stranded copper cables through an automatic oil circuit

breaker equipped with instantaneous overload trip normally set at 500 amperes. The circuit breaker thus, besides providing short-circuit protection, provides against dangerously high overloads which would result in excessive voltage drop.

The secondary side of the 2,300/460-volt bank is connected by four 500,000-circular-mil stranded copper cables through an air circuit breaker to a fused distribution board. The individual machines are connected to the distribution board by feeders whose size is based on their length in such fashion that their voltage drop at the normal maximum load shall not exceed 0.25 per cent.

The 460-volt bus is provided with a recording voltmeter and an audible undervoltage alarm signal set to operate at a $7\frac{1}{2}$ per cent drop below the normal open-circuit voltage.

Conclusion

The extensive voltage-regulation studies, extending over a period of several years, appear to indicate that the normal voltage fluctuation on the 460-volt bus is plus or minus three per cent of the average operating voltage. Under exceptional operating conditions a drop of minus four per cent has been observed. At the same time the voltage fluctuation of the 2,300-volt bus during normal operating conditions has been plus or minus two per cent of the average operating voltage.

These voltage conditions appear to be entirely satisfactory both from the plant operating and welding standpoints. For this reason the company has discontinued the use of an automatic instantaneous-operation-type voltage regulator which was originally part of this installation. The use of the voltage regulator, although it proved to be entirely practical, did not appear to be justifiable in this case as it presented certain problems and the further improvement in the voltage regulation it offered did not appear to be essential.

Company F Installation

1. Method of Service by Power Company

The power company supplies all of the load at the plant through two step-down transformer banks each rated 1,500 kva. One bank supplies all the small loads from a 120/208-volt radial system and the second bank supplies all the large loads and welders in the plant at 240 volts. The transformer banks are supplied from a 13,200-volt circuit, which is fed from two large substation busses. The entire load is metered on the primary side of the transformers and the customer owns the transformers.

2. Cost to Power Company to Serve Welder Load

No special equipment or expense was required by the power company to supply the welder loads. Voltage dip was not great enough to cause objectionable light flicker.

3. Plant Distribution for Welders

The transformer bank supplying the welders consists of three 500-kva transformers connected delta-delta of 4.4 per cent reactance and 1.7 per cent resistance. The welders are in two groups at two widely separated locations.

The first group, of which the largest welder is rated 125 kva, is supplied over a three-phase line consisting of three sets of three 800,000-circular-mil copper conductors in parallel. Other welders in the group are taken from a three-phase bus about 100 feet long made up of two one-quarter by four-inch copper conductors per phase, also supplied from the 800,000-circular-mil conductors.

The second group, of which the largest welder is 400 kva, is supplied from about 50 feet of three-phase bus made up of four one-quarter by four-inch copper bars per phase, with a spacing of one-half inch between bars. The center lines of the phases are spaced about six inches apart.

Welder-Feeder Protection

The bus to the second group, which includes the largest welders, is connected directly to the secondaries of the power transformer. The circuit to the other group is supplied through a low-voltage air circuit breaker.

Type and Rating of Welders

The largest welders in both groups are spot welders. The first group includes 21 welders having a combined rating of 1,300 kva, of which the largest is 125 kva. The second group includes 5 welders having a total rating of 1,100 kva of which the largest is 400 kva.

Voltage-Drop Data

The following calculated voltage drops at various points on the distribution system apply to 0.4-power-factor loads, which oscillograph records show to be closely approximated:

	Per Cent	
	Location 1, 800-Kva Load	Location 2, 150-Kva Load
On 13.2-kv line at the plant	1.5	0.3
On 240-volt bus	5.3	1.0
On 240-volt circuit at welder	8.0	2.0

Equivalent Thermal Heating

The timing on all of the spot welders is between 15 and 20 cycles. The time between welds is about three seconds on the larger welder and one second on the smaller group. The equivalent kilovolt-amperes on a heating basis is about 150 kva for the larger group and was about 275 kva for the smaller group.

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Industrial Notes

First Quarter Sales Increase.—Orders received by the General Electric Company during the first quarter of 1940 amounted to $97,490,047, compared with $86,882,953 for the corresponding period in 1939. Sales billed for the first 1940 quarter aggregated $85,949,194, compared with $68,537,269 during the 1939 similar quarter. . . . Orders booked by the Westinghouse Electric & Mfg. Company during the first three months of this year were $65,250,000 as against $50,121,000 for the same period last year. The company's back log of unfilled orders on March 31 was approximately $83,000,000, a peak figure in the company's history. Sales to central stations were more than 50 per cent higher than in the same quarter last year; purchases by industrial concerns were 30 per cent above the same 1939 quarter.

Appointments and Promotions.—Herbert W. Clough has been elected vice-president in charge of sales of the Belden Mfg. Co., Chicago. Mr. Clough, formerly sales manager, has been with the company for 18 years. . . . J. H. Newman has been appointed manager of district No. 1 of the General Electric wiring material sales section, with headquarters at Boston, where he was formerly a district sales representative. He replaces E. G. Hall, who has been transferred to Los Angeles. . . . Henry A. Morss, Jr. has been elected vice-president of the Simplex Wire & Cable Co., Cambridge, Mass. . . . . E. F. Meyer, formerly sales engineer with the St. Louis district office, is now in charge of the Cutler-Hammer, Inc., Houston territory, with headquarters in that city. . . . A new area sales office of the General Electric Company's plastic department has been established in Rochester, N. Y., under the direction of A. G. Davidson, Jr. as sales representative. . . . Norman L. Deuble is now assistant to the vice-president of the Copperweld Steel Co., at Warren, O. Mr. Deuble was formerly connected with the Republic Steel Corporation.

Wire and Cable Handbook.—Pocket size (4¼ by 7 inches) leatherette covered; this 270-page Simplex manual, replaces the 1930 edition which has been out of print for some time. The new edition contains a wealth of tables, formulas, and other information that should be of interest to all users of wires and cables. Includes descriptions of cables insulated with rubber, plastic, varnished cambric, and impregnated paper, and gives complete mechanical and electrical characteristics of all the various types. Included among the tables on paper insulated cables are the recommendations of the Insulated Power Cable Engineers Association and tables giving the current-carrying capacities of rubber, varnished cambric, and impregnated paper insulated cables in underground ducts of various combinations and configurations. A section entitled "Cable Engineering Data" embraces a collection of definitions, electrical units and equivalents, various formulas for cable computations, hints on the selection of the proper type of cable for various uses, line-drop formulas for various types of circuits, fault-location tests; and among the many other tables, full-load currents in motors, physical properties in metals, decimal equivalents, logarithms, and trigonometric functions. A separate section at the front of the book describes briefly the products manufactured by the Simplex Wire and Cable Co., 79 Sidney St., Cambridge, Mass., publishers of the manual.

Pole-Top Switches.—Bulletin 66, 8 pp. Describes low-cost pole-top switches for rural and distribution lines. Two types are available: PS-1 with three insulators per pole; PSA-1 with two insulators per pole. Both types are designed for double-, triple-, or four-pole units for 200 amperes, from 7,500 to 34,500 volts. Pacific Electric & Mfg. Co., 5815 Third St., San Francisco, Calif.

Test Blocks.—Bulletin 109-1, 4 pp. Describes flush-mounted, type "SJ" test blocks, conforming to flush-mounted instruments, meters, relays, etc. These devices are easily installed, of pleasing appearance, make for greater safety, and are available in 5 standard sizes. The States Co., Hartford, Conn.

Crane Speed Lowering Device.—Bulletin 990. Describes a high speed lowering device, a standardized unit applicable to any crane-hoist motor, 100 hp or less, at 230 volts, which will automatically increase the light load and empty hook speeds of cranes as much as 80 per cent. The Electric Controller & Mfg. Co., Cleveland, Ohio.

Unit Heaters.—Bulletin GEA-2592A, 8 pp. Describes forced- and natural-convention types of electric unit heaters. General Electric Co., Schenectady, N. Y.

Insulators.—Bulletin 702-H, "Conduction-Glazed Silentype Insulators". Includes complete catalog information on multipart, unipart, and small pintype insulators treated with a metallic underglaze to keep them from causing radio interference. Ohio Brass Co., Mansfield, Ohio.

Drafting Machine.—Booklet, 16 pp. Illustrates and describes a new improved Paragon drafting machine, which has been completely re-designed. The major principles of the original model have been retained, but 11 refinements and 5 exclusive improvements have been incorporated that greatly simplify the process of mechanical drafting. Keuffel & Esser Co., Hoboken, N. J.

Equipment Guide.—"Quick Selector" Catalog (30–000), 64 pp. Prepared especially to facilitate the selection of apparatus for any motor, lighting, or feeder circuit. Safety switches, No-Fuze breakers, multibreakers, distribution panelboards, motors, and motor controls are featured in successive sections of the catalog. Four pages of general application data contain NEC recommended installation practices. Electrical ratings, physical dimensions, and individual circuit diagrams for the various devices are included. Cost information is given for each item. Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

Trade Literature

Capacitors.—Bulletin GEA-2742A, 24 pp. Describes Pyranol capacitors for low-voltage industrial applications, 230, 460, and 575, volts, and for indoor and outdoor service. General Electric Co., Schenectady, N. Y.

Graphic Wattmeter.—Bulletin 939, 4 pp. "What You Can Do With a Graphic Wattmeter". Describes and illustrates numerous applications of such meters. The Esterline-Angus Co., Inc., Indianapolis, Ind.

Electrical Contacts.—Bulletin F-101, 4 pp. Describes various types of silver-nickel contacts for use in electrical equipment. Designs and mechanical and electrical characteristics are included. Gibson Electric Co., 443 Boulevard of the Allies, Pittsburgh, Pa.

WANTED: Copies of the September (1939) issue of ELECTRICAL ENGINEERING. Please mail (parcel post) to American Institute of Electrical Engineers, 33 W. 39th St., New York City, printing your name and address upon the enclosing wrapper. Twenty-five cents, plus postage, will be paid for each copy returned.

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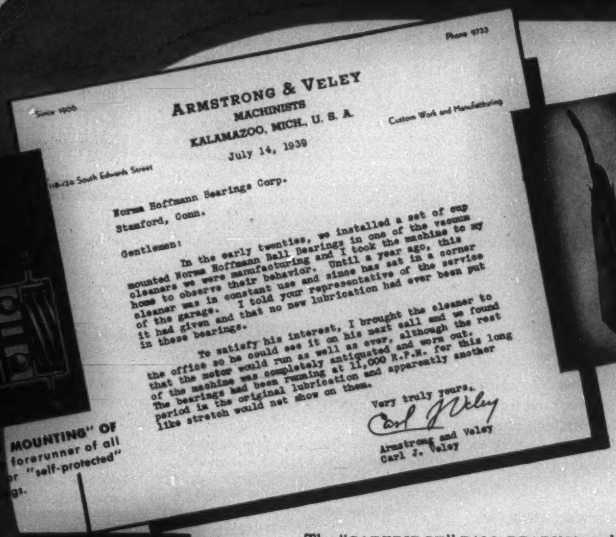

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July 14, 1939

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To satisfy his interest, I brought the cleaner to the office so he could see it on his next call and we found that the motor would run as well as ever, although the rest of the machine was completely antiquated and worn out. The bearings had been running at 11,000 R.P.M. for this long period in the original lubrication and apparently another like stretch would not show on them.

Very truly yours,
Carl J. Veley
Armstrong and Veley
Carl J. Veley

THE "CARTRIDGE" BALL BEARING OF TODAY with the large grease-capacity feature incorporated in a simple and improved unit

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The "CARTRIDGE" BALL BEARING embodies the same sound, basic principle of extra large grease capacity that was provided in the "Cup Mounting", originated by NORMA-HOFFMANN in 1921 and referred to in the above letter.

It has TWICE THE GREASE CAPACITY OF ANY OTHER SINGLE-ROW ANTI-FRICTION BEARING, with a reservoir of grease providing abundant lubrication to raceways and rotating elements at all times. Grease cannot escape, and dirt cannot enter its flanged, wearless seals—either while the bearing is being mounted or is in service. The "CARTRIDGE" BALL BEARING IS AN INTEGRALLY SEALED UNIT, NEEDING NO SUPPLEMENTARY CLOSURE PARTS WHATEVER. Therefore, it affords easier and quicker assembly and disassembly, and eliminates many costly extra parts and machining operations. It has convenient regreasing and inspection features. It is simplicity itself.

We do not indiscriminately recommend any self-sealed bearing as being lubricated for the life of the unit. Nevertheless such a record as is reported above proves that LARGE GREASE CAPACITY DOES PROLONG BEARING LIFE. The "CARTRIDGE" BALL BEARING, therefore, with 100% greater grease capacity, is your best assurance of long, uninterrupted performance.

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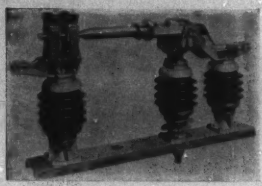
New Products

High Pressure Contact Switch.—In the new, type "MK-39", high pressure contact switch announced by the Delta-Star Electric Company, Chicago, the blade mechanism not only converts the rotating motion of the operating insulator to the vertical swinging of the blade, but it also turns the tubular blade to make high pressure contact. The blade hinge end also has high pressure contacts. By means of a "high spotted" cam, high pressure is created in the closed position only. In the entire mechanism there are but four bearings. There are no stops to limit the swing of the blade as it approaches closing position just before final turning or twisting movement to make high pressure contact, thus insuring smooth operation without shocks or jars to the porcelain in-



sulators. The new switch is available in all voltages up to 161 kv, and current capacities up to 2,000 amperes. Cemented cap and pin insulators, with tapped or slotted caps, or station post units with tapped or slotted cap and base are furnished, as preferred.

Extruded Tubing.—A new development in plastic materials is an extruded tubing manufactured in continuous lengths by the Irvington Varnish & Insulator Co., Irvington, N. J. It is said to possess outstanding mechanical strength, improved tear and abrasion resistance, extreme flexibility, greater solvent and heat resistance, and is more fireproof than any former similar type of material. It is particularly fitted for use in the automotive, aviation, communications, electrical, instrument, marine, radio, and other fields where flexible tubing plays an important part in insulating conductors against heat, moisture, oils, etc. The new product, known as "Irv-O-lite Type XTE-30", is produced in five standard colors from size No. 20 to $\frac{5}{8}$ inches, and can be manufactured in different sizes and wall thicknesses as specified.

Mobile Capacitor Unit.—A portable, trailer-mounted capacitor equipment, which can quickly be moved to any substation on the

utility's system in case of an emergency, was recently built at General Electric's Pittsfield (Mass.) works for the Pennsylvania Power & Light Co. Completely assembled at the factory, the equipment has automatic control for varying the kva as demanded by circuit voltage conditions. The mobile unit is believed to be the first of its kind. The automatically switched equipment is rated 1,080 kva, 2,300 delta 4,000 Y volts, three-phase, 60 cycles. It consists of three sections of 190, 360, and 540 kva. By proper control, using a contact-making voltmeter as the master element, six capacitance steps are available: 180, 360, 540, 720, 900, and 1,080 kva. Total weight of the capacitor equipment is more than 14,000 pounds. The apparatus is mounted on a standard, high-speed, 8-wheel type trailer, which will connect to a tractor-truck. The power company's area is about 9,300 square miles.

Wet Electrolytic Condensers.—To meet the higher voltage requirements encountered in some applications, three new types of wet electrolytic condensers are now produced by

the Aerovox Corporation, New Bedford, Mass. These units are available in 4-, 8-, and 16-mfd capacities, with a 600-volt d-c surge rating, as compared with 350- and 500-volt ratings heretofore available. Can sizes are $1^{3}/_{8}$ and $1^{1}/_{2}$ inch diameter, and $3^{7}/_{16}$, $4^{7}/_{16}$ inches high. The ability of these condensers to withstand higher surge voltages, and to reform if momentarily broken down by excessive voltages, and to operate at higher voltage under steady operating conditions, makes them particularly applicable in circuits subject to violent surges.

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Limiting its activity solely to the making of electrical wires, cables and accessories, General Cable carries the processes of manufacture through every step in its own plants. General Cable rolls its own copper rods, draws its own wire, creates its own insulating compounds, and does all those many other things involved in the manufacture of electrical conductors. Through every step, quality is held to standards prescribed by the General Cable Research Department and maintained within the same exact limits in all company plants. Uniformity of quality has been an outstanding advantage of General Cable Wires and Cables.

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The Type KB circuit breaker establishes an arc so promptly and quenches it so efficiently that the interrupting ability is not only high but the interruption can take place within a non-ventilated, dust-proof enclosure.

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The Type KB is very conservatively rated at 20,000 amperes. The factor of safety between rated capacity and the actual ability to interrupt high currents has been greatly increased.

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A number of years ago, I-T-E foresaw the need for a circuit breaker which would combine some motor-starting contactor characteristics with those of a circuit breaker. The result was the development of a circuit breaker, known as the Type K, which has been dominant in the field of circuit protection for services up to 250 volts d-c and 600 volts a-c.

The new Type KB is a complete new design of the Type K. A thoroughly reliable, time-proved circuit breaker has been made to produce an even better standard of performance. The factor of safety between rated interrupting capacity and the actual ability of the device to interrupt high currents has been greatly increased. The Type KB circuit breaker has a more conservative rating than any circuit breaker we have ever built.

The new designs were developed with variety of service requirements in view. Operating characteristics are readily adapted to specific needs. At the same time, the designs provide a new measure of convenience and flexibility in mounting and in operation.

After fifty-one years of pioneering in the development of circuit breakers, in which period this company has worked exclusively with air-immersion, I-T-E recommends that the features of the new Type KB circuit breaker be reviewed as improvements based on experience.

Send for Bulletin 4001

which outlines and illustrates the essential features of the new Type KB.

I-T-E

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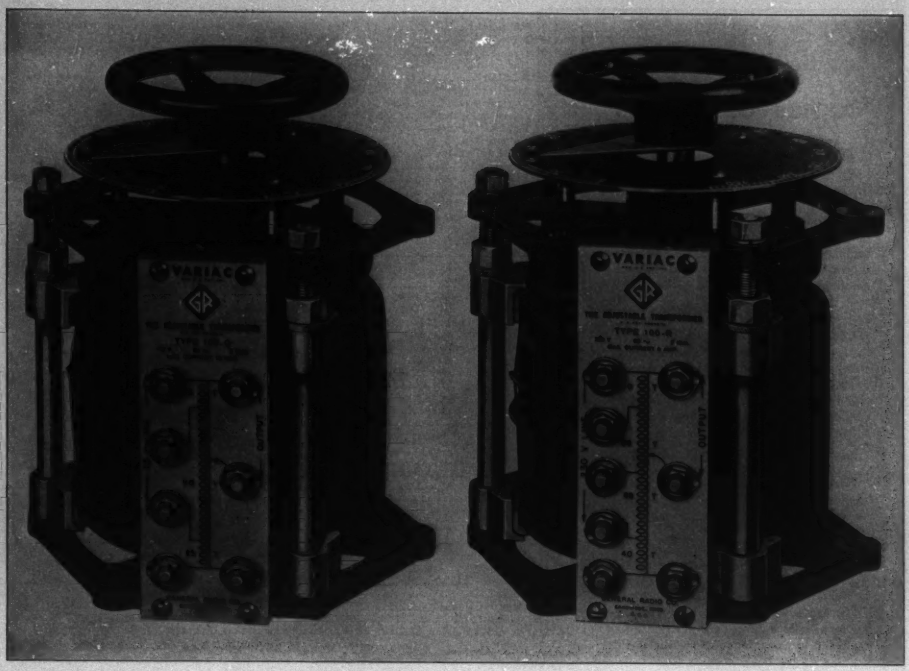

Type 100-Q and Type 100-R

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THE TWO MODELS of the Type 100 Variac, illustrated, are very popular for medium power use. Designed for maximum continuous loads of 2 kva, the new Type 100 is in general similar to the former 2 kva models except that bigger cores are used, output voltages 15% above line voltage can be obtained, improved terminal plates include wiring diagrams, pigtails are provided to reduce heating of brushes and longer brush springs maintain uniform tension.

The Type 100-Q VARIAC supplies continuously adjustable output voltages from *zero* to *135* volts on a 115-volt circuit, with a rating of 18 amperes.

The Type 100-R VARIAC supplies output voltages continuously adjustable from *zero* to *270* volts from a 230-volt line, with a rated current of 9 amperes.

Both models are supplied with reversible calibrated dials and with terminals so that either a maximum output voltage equal to the line voltage or equal to the above "higher-than-line voltages" may be obtained.

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Summer Convention

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☐ 39-112	Race	Dielectric Strength of Insulating Liquids
☐ 39-113	Race	Tests on Oil Impregnated Paper—IV
☐ 39-116	Harrison	Ionization Time of Thyratrons
☐ 39-120	St. Clair*	Multiwinding Transformers with Synchronous Condensers
☐ 39-121	Marti & Taylor*	Wave Shape of 30- and 60-Phase Rectifier Groups
☐ 39-122	Lewis & Foust*	Lightning Investigation on Transmission Lines
☐ 39-123	Alford & Pickles*	Radio-Frequency High-Voltage Phenomena
☐ 39-127	Benson & Strang	12-Kv Metal-Enclosed Bus and Switch Structure
☐ 39-129	Halperin*	Testing of Distribution Arresters
☐ 39-134	Malti & Herzog	Fractional-Slot and Dead-Coil Windings
☐ 39-136	Dickerson & Mahan	Painting the Golden Gate International Exposition With Light
☐ 39-137	Kittie*	New Type of D-C to A-C Vibrator Inverter
☐ 39-138	Davis*	Signal System, San Francisco-Oakland Bay Bridge Railway
☐ 39-139	Hanna & Tritle	Electrical Equipment of the Steam-Electric Locomotive
☐ 39-140	Reinitz & Wiseman*	A New Technique for Lead Cable Sheathing
☐ 39-141	Smith & Tenney	Temperature Survey of the United States
☐ 39-144	Aggers, Foster & Young*	Instruments and Methods of Measuring Radio Noise

Minneapolis Meeting

☐ 39-147	LeClair*	Arc-Furnace Loads on Long Transmission Lines
☐ 39-148	Summers*	An Unstable Nonlinear Circuit
☐ 39-149	Foust & Rohats*	Developments in Impulse-Voltage Testing
☐ 39-150	Peterson, Rudge, Monteith & Ludwig*	Protector Tubes for Power Systems
☐ 39-151	Fountain, Dissmeyer & Elzi	Co-ordination of Control of Synchronous-Machine Excitation
☐ 39-152	Maxfield, Hegbar & Eaton	Importance of Gas in Electrodes for Glow-to-Arc Transition
☐ 39-153	Swanson	Polarized Field Frequency Control of Synchronous Motors
☐ 39-154	Smith & Bostwick	Ratio Differential Protection of Transmission Lines
☐ 39-155	Hoard*	Transit-System Modernization, Choice of Vehicle
☐ 39-156	Bryant & Newman	Electronic Measurement of Surge-Crest Voltages
☐ 39-157	Bryant & Newman	Measurement of Very Short Time Lags
☐ 39-158	Butler	Factors Influencing Shunt Capacitor Equipments
☐ 39-159	Holbrook & Dixon*	Load-Rating Theory for Multichannel Amplifiers
☐ 39-160	Kurtz	Dynamic Characteristics, Single-Phase Induction Motor
☐ 39-161	Parsons	Vaults for A-C Secondary Networks
☐ 39-162	Stephens & Gehrenbeck	Corrosion of Fine Copper Wires Carrying a Potential
☐ 39-163	Willey	Emergency Radio as Safeguard to Telephone Service

Scranton Meeting

☐ 39-164	Renshaw*	Mercury-Arc Rectifiers in Coal Mining
☐ 39-165	Bell	Lightning Investigation on a 220-Kv System, III
☐ 39-166	Baldwell	Electrical Apparatus in the Steel Industry
☐ 39-167	Armstrong*	NEMA Resistors for Motor Starting and Speed Control
☐ 39-168	Penney	Temperature Rise of Electrical Apparatus
☐ 39-169	Compton	Class B Insulation for Auxiliary-Type D-C Motors
☐ 39-170	Edmunds	Adjustable-Speed A-C Motors
☐ 39-171	Beavers	Selection of Distribution-Transformer Size
☐ 39-172	Hentz & Thielman	Power Supply for Suburban Areas
☐ 39-173	Camilli	Current-Transformer Design

Winter Convention

☐ 40-4	Torchio	Railway Power Supply
☐ 40-5	Bellaschi & Palermo	Analysis of Transient Voltages in Networks
☐ 40-6	AIEE Committee Report	Report on Power Generation
☐ 40-7	Alexanderson, Edwards & Bowman	Dynamoelectric Amplifier for Power Control
☐ 40-8	Foust & Scott	Breakdown Tests on Oil-Treated Paper-Insulated Cable
☐ 40-10	Fisher	The Design Characteristics of Amplidyne Generators
☐ 40-12	Morgan, Brown & Schumer	Induction Motor Characteristics at High Slip
☐ 40-13	Morrill	Harmonic Theory of Noise in Induction Motors
☐ 40-14	Wynne & Woods	The Application of Traction Motors
☐ 40-15	Noertker	Problems of Electrical Engineering in Transportation
☐ 40-16	Marti	Static Electronic Frequency Changers
☐ 40-21	Balsbaugh, Howell & Dotson	Generalized Bridge Network for Dielectric Measurements
☐ 40-23	Shoults, Edwards & Crever	Industrial Applications of Amplidyne Generators
☐ 40-25	Lusignan & Miller	What Wood May Add to Primary Insulation
☐ 40-26	Evans, Gulliksen & Myhre	Synchronizing Transients and Synchronizers
☐ 40-27	Hill	Power Supply for Railroad Electrification
☐ 40-28	Craton & Turner	Electric Braking for Railroad and Urban Transit Equipment
☐ 40-29	Withington	Trends in Railroad Motive Power
☐ 40-34	Davis & Eddy	Impulse Strength of Cable Insulation
☐ 40-36	Sporn & Gross	Rationalization of System Insulation—III
☐ 40-37	AIEE Committee Report	Proposed Standards for Outdoor Bushings
☐ 40-38	AIEE & EEI-NEMA Joint Report	Recommendations for High-Voltage Testing
☐ 40-39	Clark	The "Speedomax" Power-Level Recorder
☐ 40-40	Faucett, Kreener & Helm	The Accuracy of Watt-Hour Meters on Intermittent Loads
☐ 40-41	Goss & Hansen	Rotating Standard for the Measurement of Kilowatt-Hours
☐ 40-42	Weller, Trekell & Stebbins	Watt-Hour Meter Performance with Power Rectifiers
☐ 40-44	Bowles, Barrow, Hall, Lewis & Kerr	The Microwave Instrument Landing System
☐ 40-45	Alford & Kandoian	Ultrahigh-Frequency Loop Antennas
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☐ 40-54	Untersee	Power Requirements of Spinning Frames—II
☐ 40-58	AIEE Committee Report*	Power Supply for Resistance-Welding Machines—I
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* *Has been published in the* TRANSACTIONS *section of* ELECTRICAL ENGINEERING.

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Installed cost of moderate-duty metal-clad 25,000 and 50,000 KVA capacities is little more, if any, above other forms of construction. This type gear gives the following advantages:—

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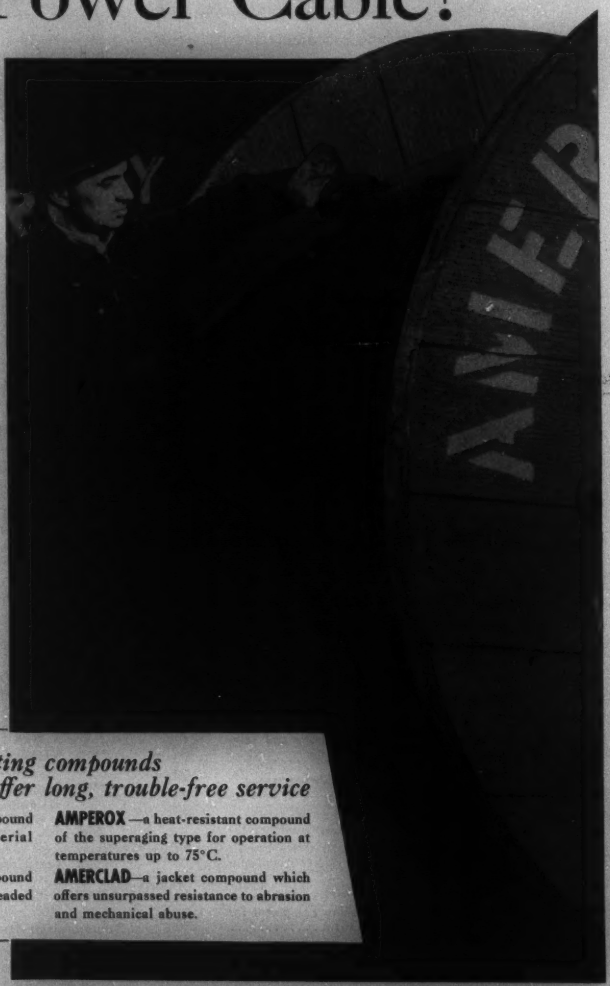
For Example: Back in 1909, American Steel & Wire Company made the first non-leaded submarine cable, insulated with a special water-resistant compound since called Amarine. That cable, after conducting power at 25 KV across the St. Lawrence River for 31 years, when inspected recently, was found to be "still in excellent condition, good for many more years of service."

That's 31 years of immersion in water and mud, of direct burial of shore ends in acid and alkaline soils, and of exposure of pole risers to extremes of heat and cold—the same conditions, in exaggerated degree, that are found in many less exacting applications.

Here is real proof that American Steel & Wire Company knows how to engineer and manufacture cables for long, trouble-free service.



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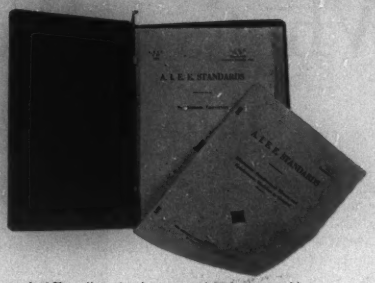

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Seven such sections are now available in report form for purpose of criticism, and copies will be sent without charge upon request. These sections are as follows:

No. 6 Mercury Arc Rectifiers.	501 Test Code for D-C Machines.
25 Fuses Above 600 Volts.	40 Electrical Recording Instruments.
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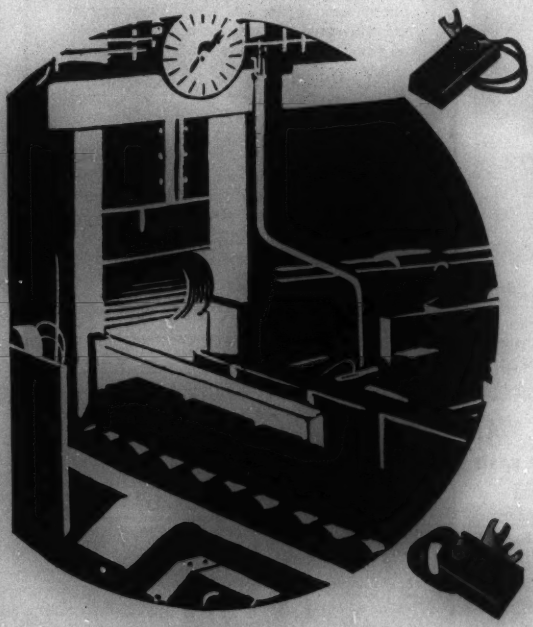

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● Adaptability of the product to the service on which it is applied is the key to reliability of performance. "National" Carbon Brushes are designed for adaptability to specific machine characteristics and service conditions. There are several "National" grades designed specifically for the conditions encountered in steel mill service.

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OF THE WONDERFUL
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(That was built in such a logical way
It ran a hundred years to a day)"

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Our flexible manufacturing facilities enable us to make prompt shipment and to quote low prices on special equipment manufactured to your specifications and adapted to your requirements.

For example, synchronous motors, 1 to 15 horsepower; direct current generators with wide voltage range with separate excitation obtained from rectifier or other source; high ampere low voltage direct current generators; odd frequency alternating current generators and frequency changers; laboratory power supply panels with wide range of control to give 115, 230 and 600 volts A.C. and D.C.

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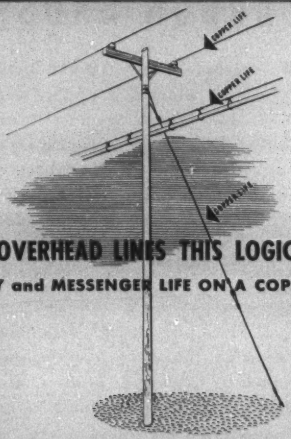

BUILD OVERHEAD LINES THIS LOGICAL WAY
PUT GUY and MESSENGER LIFE ON A COPPER BASIS

There are traces of age in the one-hoss shay,
A general flavor of mild decay,
But nothing local, as one may say.
There couldn't be,—for the Deacon's art
Had made it so like in every part
That there wasn't a chance for one to start.
. . .
Logic is logic. That's all I say.
Oliver Wendell Holmes (1858)

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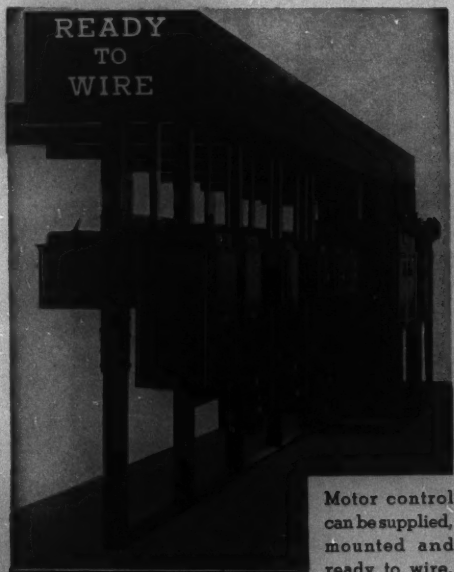

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THE ROWAN CONTROLLER CO., BALTIMORE, MD.

Motor control can be supplied, mounted and ready to wire. Send us your specifications.

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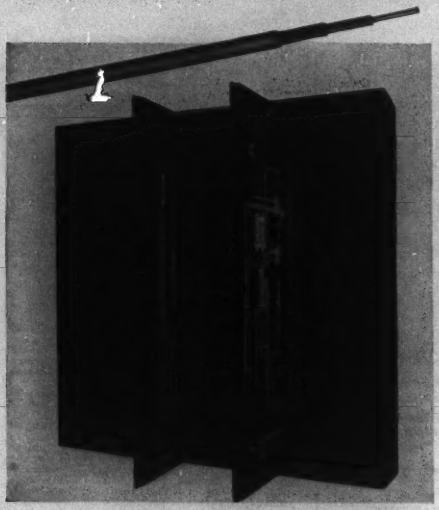
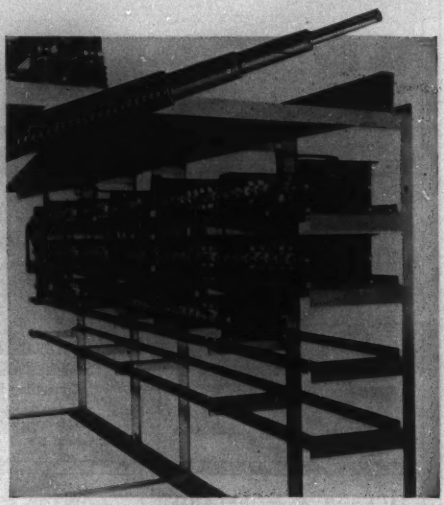


DELTABESTON SWITCHBOARD WIRE

Won't burn—Waterproof—Extremely flexible—Cuts wiring time—Facilitates installation due to smaller over-all diameter—High dielectric strength due to synthetic insulation—Takes sharp bends easily, without harm to insulation.



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Outstanding heat resistance—Easy to work with—Tinned copper conductor—Synthetic insulation—Felted, purified asbestos layer, flame-, heat-, moisture-resisting—Purified asbestos outer braid.

STATION CABLE

Built for a particular central station application—Answers four demands:

1. Permits high current densities during peak load periods.
2. Resists extreme ambient temperatures.
3. Flameproof insulation—isn't damaged by severe treatment.
4. Interlocking armor eliminates need for rigid conduit.

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A weekly bulletin of engineering positions open is available to members of the co-operating societies at a subscription of $3 per quarter or $10 per annum, payable in advance.

In the interest of effective service, it is essential that members using the employment service keep the bureau office serving them advised at reasonable intervals concerning their availability for employment, concerning any change in status, and immediately upon acceptance of any employment.

Employers interested in the following announcements should address replies to the key numbers indicated, and mail to the New York office.

Men Available

ELEC DES AND COST ENGR; degree; 20 yrs exper; licensed prof engr, N. Y. State; util, architects, consulting engrs, contractors, govt work, specialist on wiring for all types of bldgs. Desires pos anywhere U.S. Available May. E-630.

GRAD E.E., 37, married; 17 yrs exper pwr plant, mine, mill, smelter; can handle men and get results. Location optional. Available June 1, 1940. E-631-403-C-4-San Francisco.

B.S.E.E., 1935, M.S., 1938, Lehigh Univ; 28, single. 2 yrs asst instructor; previous exper in indus. Desires engg pos with pwr co or elec mfg co. E-632.

JR ELEC ENGR, B.S.E.E., U.S.C., 1937; 26, married; 3½ yrs oil refinery exper; elec draftg, des; pwr factor studies; instal, maintenance, repair elec apparatus, transm lines. Desires pos pwr generation, transm. Available immed; location immaterial. E-633-403-C-3-San Francisco.

B.S.E.E., 1930, M.B.A., 1933, Univ Kansas; 32, married; 4 yrs util, 3 yrs contractor, cost estimator on transm, distr, substations, underground, field exper. G.E. test course. Desires estimating or constr work. E-634.

B.S., M.S., Case, 1936; 23, single; 2 yrs universal motors and appliances; desires pos in elec specialties, lt eqpt or col teaching. Interested in product des, devpmt, circuit theory. E-635.

ASST ENGR, grad Pratt Institute; married; 16 yrs study to personnel problems while employed on large util co having mfg subsidiary. Desires pos in technical personnel selection or placement. E-636.

E.E., 1930, Rensselaer Polytechnic Institute; single; 4 yrs exper air conditioning and temperature control. Desires pos in this or other line. Location, in or near New York City. E-637.

B.S. E.E., 1937; 27, married. Eta Kappa Nu. 3 yrs in charge of appliance dept. Desires change to draftg and des with mfr or util. Location, immaterial. E-638.

B.S. in E.E., 1939, So. Dakota State School of Mines; 26, single; exper in treatment of boiler feed water. Desires pos with util co or consulting engr. E-639-163-Chicago.

B.S. in E.E., 1938, U. of Wisconsin; 24, married; 2 yrs exper machine changeovers, spot, projection, butt welding; electronic, air control, elec maint. Desires pos mfg industry with engg future. Now employed. E-640-357-Chicago.

E.E., middle-aged, excellent health, extensive exper large, small concerns, devpmt, shop, sales, chief engr several small cos. Listed "Who's Who in Engineering". Now employed Government, desires return industry. E-641.

LICENSED PROF ENGR IN ELEC, INDUS ENGG; 2 degrees, Ohio State. Exper both fields covers 13 yrs. Desires better connection in prod, preferably elec products. Location, East or M.W. E-642.

PWR AND LT EXEC, 42, married; 20 yrs constr, oprn, maintenance hydro-elec, steam-elec plants and substations; 2 yrs Porto Rico. Location immaterial. E-643.

B.S.E.E., N.Y.U., 1936; 25, single; 3 yrs experimental lab, motors, generator and various apparatus; studying motor des; now employed, desires pos with elec mfg or util with future. E-644.

B.S.E.E., 1935, M.S., 1940; 26, married; Tau Beta Pi, honors. One yr devpmt test of fractional hp mach; 3 yrs asst instructor. Employed. Desires pos in teaching or indus devpmt. E-645.

B.S.E.E., S.M.U., 1933; 28, married; 9 yrs exper with oil refinery and large util; system planning, des, economic studies, supervision overhead and underground constr. Desires permanent connection. Available immed. E-646.

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Bartaps

JOIN CABLE TO FLAT BAR—WITH ONLY A WRENCH!

This Burndy Bartap eliminates the delay and expense of drilling bolt-holes for cable-to-bar connections: a few turns with a wrench and the job is done!

Bartaps are available for any number or combination of bars and cables. Name YOUR need!

The Burndy Bartaps shown at the left connect two cables to flat bar.

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VARNISHED CAMBRIC • RUBBER COVERED POWER CABLES • BUILDING WIRE • SIGNAL CABLE • FLEXIBLE CORDS • ARMORED CABLE • SERVICE ENTRANCE CABLE • MAGNET WIRE •

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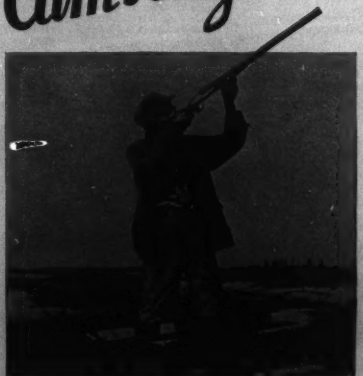
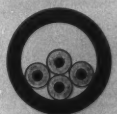
SMALL DIAMETER BUILDING WIRES



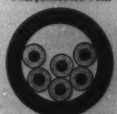
As you well know, the changes in the new National Electrical Code open up great opportunities for the rewiring of existing "bottle-neck" branch feeders.

For this rewiring, it will pay you to specify CRESCENT ENDURITE Rubber Insulated Type RHT and CRESCENT SYNTHOL Synthetic Insulated Type SN SMALL DIAMETER BUILDING WIRES which are unexcelled in quality, ease of installation and permanence.

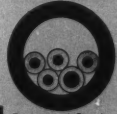
Two typical examples of the increase in capacity possible in existing ½" conduit are shown in the two lower figures on the right.



Four #14 Type R Code Wires permit 3450 Watts



Six #12 Type RHT Small Diameter Wires permit 7450 Watts



Four #12 and One #10 Insulated neutral Type RHT permit 8100 Watts

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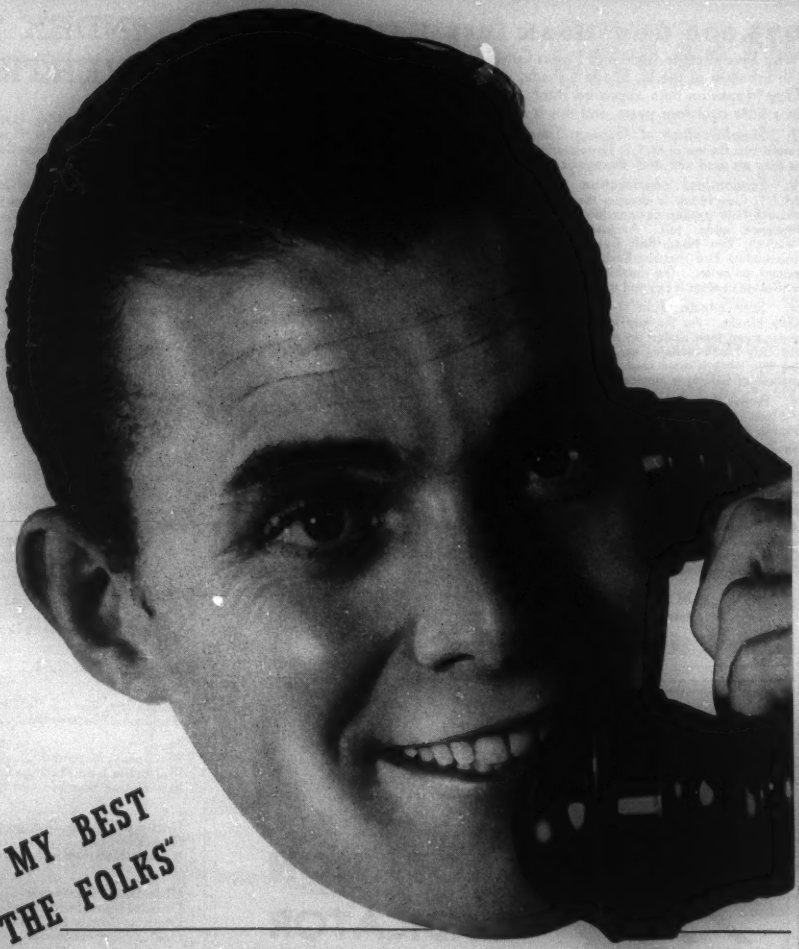

"GIVE MY BEST TO THE FOLKS"

"Hope to be seeing you soon." . . . "Gee, it's swell to hear your voice." . . . "We're all well here."

No great words of business or state are these—just the homey, every-day conversations that are America. The thoughts and hopes and remembrances that bind families and friends together. The flow of understanding that helps to make this a united nation.

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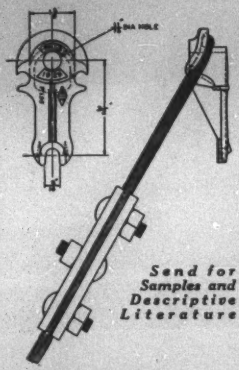

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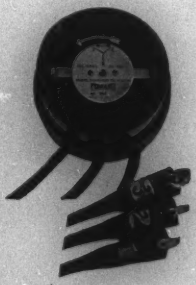

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2½" Portable Model
110-550 volts

●

Flush and Surface Types also available

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Send for complete descriptive data!

The Ferranti Phase Rotation Indicator is provided with insulated clips numbered, 1, 2 and 3 which distinguish phase to which they should be attached.

Direction of disc rotation tells immediately if phase rotation is correct. Indispensable where metering equipment is involved in 3-phase supply. Invaluable also for correctly marking bus bars and leads.

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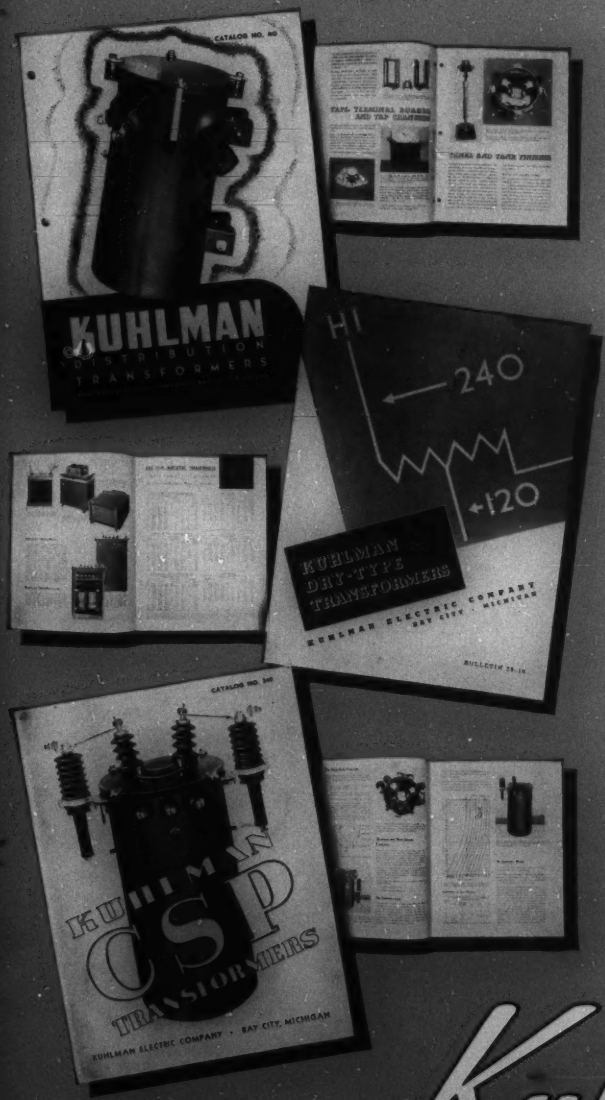
3 NEW KUHLMAN CATALOGS

THAT EVERY ELECTRICAL ENGINEER SHOULD HAVE



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Kuhlman

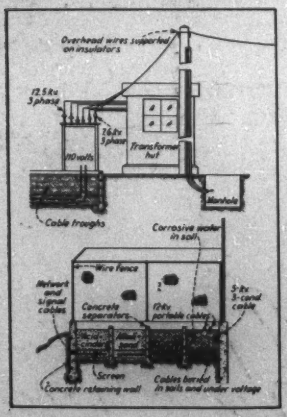
PROVING GROUND PROVIDES CHECK ON CABLE PERFORMANCE

Improved Cable Designs Result from Study of Operating Behavior

Concentrated in the Okonite proving ground are all the destructive elements that attack insulation. Overhead cables are exposed to weather conditions or buried in "graves" filled with soil, impregnated with chemicals, sewage and other corrosive agents.

Here, under full load and voltage—duplicating the severest service conditions in every way — cables stay for years.

Arrangement of troughs and high-voltage bus structure in Okonite's proving ground.



Okoprene-protected riser cables, Okolite high-voltage rubber-insulated cables installed on messenger, Okolast tree wire, as well as various other types of overhead cables under comparative test in Okonite's Proving Ground.

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Founded 1878

EXECUTIVE OFFICE: PASSAIC, NEW JERSEY

HAZARD INSULATED WIRE WORKS DIVISION

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